Preoperative CT and Intra-Operative Physical Space Registration of the Spine Using an Articulated Model: a Phantom Study

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A B S T R A C T

Purpose: Due to the difference in spine curvature in intra-operative and preoperative situations in image guided spine surgery (IGSS), each vertebra needs to be registered separately. This can be done by collecting anatomical landmarks on the patient's anatomy using a pointer and a tracker, and registering them with corresponding points on the 3D model of CT images. Registering each vertebra using this method can be a tedious and time consuming task. Registering the spine using an articulated model, which incorporates the inter-vertebral transformation between consecutive vertebra, introduces a simple and efficient framework.

Methods: In this paper, a deformation (extension) is applied to the lumbar vertebra of a spine phantom. Local coordinate systems are defined separately for each vertebra in the 3D model reconstructed from CT images before deformation and on the phantom after deformation. The intervertebral transformations for consecutive vertebrae are calculated in the 3D models. Registration is carried out using the local coordinate systems and the intervertebral transformations.

Results: This method was evaluated using point based registration with known corresponding points in both spaces. These results were also compared to those of surface based registration. As indicated by the results, an average improvement of 30% in the registration accuracy was achieved compared to the surface based registration method with acquired random points.

Conclusion: The proposed method decreases the registration time by eliminating the need to acquire surface points on each individual vertebra. It is also applicable in situations with defected vertebrae where anatomical landmarks are difficult to distinguish.

1. Introduction

Image guided interventions have increased the accuracy of surgical procedures to a great extent [1]. A key step in image guided interventions is the registration of preoperative images to the intra-operative physical anatomy of the patient, which can be carried out by matching corresponding landmarks in both spaces. In order to be able to track surgical tools relative to the patient's anatomy in real time an accurate registration of pre-operative images to the intra-operative space is required. A rigid registration is carried out to bring the set of corresponding points in one coordinate system. Point based registration is an efficient method used for rigid registration [2-6]. Corresponding anatomical landmarks are selected in CT images and acquired on patient's physical anatomy using a tracked probe.

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Two types of landmarks can be used for bringing the two coordinate systems into alignment: Fiducial markers attached to specified locations of the anatomy, and anatomical landmarks which are distinct points on the anatomy. In neurosurgery the alignment of the two coordinate systems can be done by a combination of anatomical landmarks and markers attached to the head before imaging and throughout the procedure. A rigid registration is carried out to bring the sets of corresponding points in one coordinate system. In the case of spine surgery, anatomical bony landmarks are used for initial aligning of the two point sets [7].

The accuracy of pedicle screw placement in spine surgery is of great importance due to the crucial neuro-vascular structures surrounding the spine [1]. Image guided spine surgery (IGSS) has improved this accuracy to a great extent. Many studies [8-11] have contributed to the registration of preoperative CT images of the vertebrae to patients' intra-operative physical space which register each vertebra separately using point based and surface based registration methods. As the spine is a non-rigid body but each vertebra is rigid, rigid registration is applied to each vertebra separately to compensate for the deformation in spine curvature in pre and intra-operative conditions in IGSS. Many studies have contributed to the registration of preoperative images and intra-operative position of the spine in spinal navigation systems. Some of these studies register the preoperative CT images to the patient's physical space using data points selected on the anatomy in the intra-operative situation and some use an imaging modality for the intra-operative data. Herring et al [9] proposed the registration using a surface based method which registered each vertebra separately. Tamura et al [10] studied the accuracy of surface based method. Rasoulain et al [12] proposed a group-wise method for the registration of the preoperative CT images to intra-operative ultrasound images. They used a biomechanical model to constrain the vertebra motion during registration.

This study presents a framework to register the preoperative images to the patient's intra-operative position using both surface information from the vertebra and the intervertebral transformation. The registration between the 3D model reconstructed from CT images and the physical space is carried out using the articulated model for spine proposed by Boisvert et al [13]. In this model, local coordinate systems are defined for each vertebra using some anatomical landmarks. Then, the intervertebral transformations between consecutive vertebrae are calculated using a rigid registration.

Collecting anatomical landmarks on each vertebra to perform the surfaced based registration can be a tedious and time consuming task. Therefore, registering one vertebra and being able to register the other vertebrae by the known inter-vertebral transformation between consecutive vertebrae can introduce an effective framework. In addition, finding anatomical landmarks on defective vertebra is difficult or even impossible in some situations; thus, being able to register these vertebrae by registering the adjacent vertebrae and having knowledge of intervertebral relations can be useful.

2. Methods

In this section, the proposed registration method is outlined. Firstly, the CT images were acquired and the 3D model was reconstructed from these images. Then, the intervertebral transformations were obtained using the local coordinate system defined for each vertebra. Next, registration was carried out using the intervertebral relations between the consecutive vertebrae. Finally, this method was evaluated using point based registration as the highest performance method.

2.1. Phantom Setup and Data Acquisition

This study was carried out on a spine phantom. The lumbar vertebrae of a spine phantom were fixed using a holder mechanism which completely fixes the desired orientation and prevents any movement during all steps of the experiment (Fig. 1a). A deformation was applied to these vertebrae to simulate the difference in the spine curvature between the pre and intra-operative situations. CT images were acquired with axial slices of voxel size $0.625 \times 0.625 \times 0.625$ mm and 3D models were constructed from CT images. The 3D models before and after deformation are shown in Fig 1b, 1c. The 3D model reconstructed from CT images was carried out automatically using Amira®[1] where a robust and fast surface reconstruction algorithm is applied which triangulates all grid cells individually, similar to the marching cubes algorithm for computing isosurfaces.

A local coordinate system was defined for each vertebra. In order to obtain the local coordinate systems for each vertebra, three points (the spinous process and the left and right transverse process Fig. 2) were acquired on each vertebra of the spine phantom using Parsiss©[2] surgical navigation – Image Vision system [14] and also on the 3D model.

1. Amira is being jointly developed by Konrad-Zuse-Zentrum f`ur Informationstechnik Berlin (ZIB) and

2. Visage Imaging http://parsiss.com/main.php

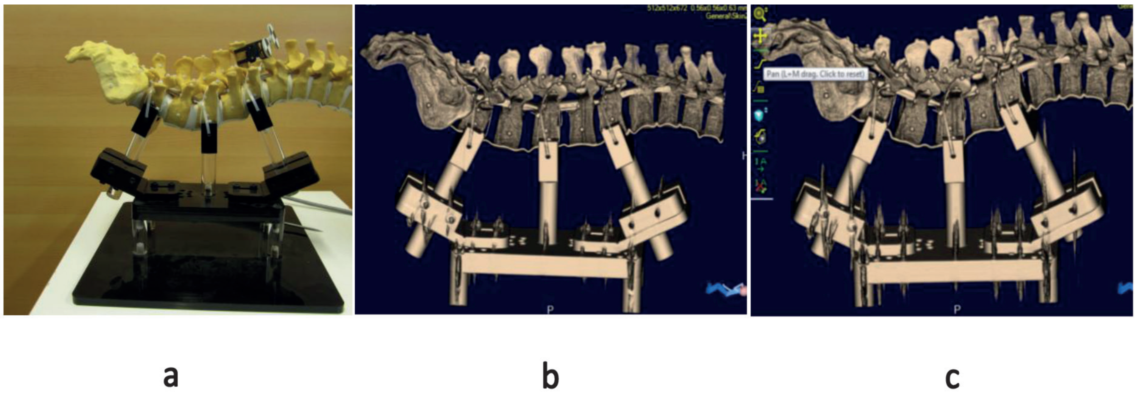

Figure 1. (a) Spine phantom, (b) 3D CT model before deformation, (c) 3D CT model after deformation.

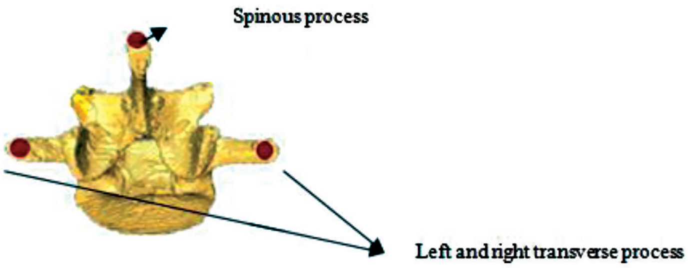

Figure 2. the spinous process and the left and right transverse process used to obtain the local coordinate system for each vertebra.

2.2. Registration Using Intervertebral Transformation

As mentioned in the previous section, a local coordinate system was defined for each vertebra using three points on each vertebra. The three points were used to obtain two vectors where one of them was the first axis of the coordinate system; a vector perpendicular to these two vectors was obtained by their cross product constructing the second axis of the coordinate system and, then, the third axis was obtained by the cross product of the first and second axis; this is shown in Fig. 3a. The transformation (T) matrix between the local coordinate system of each two consecutive vertebra (Fig. 3b) was calculated as follows.

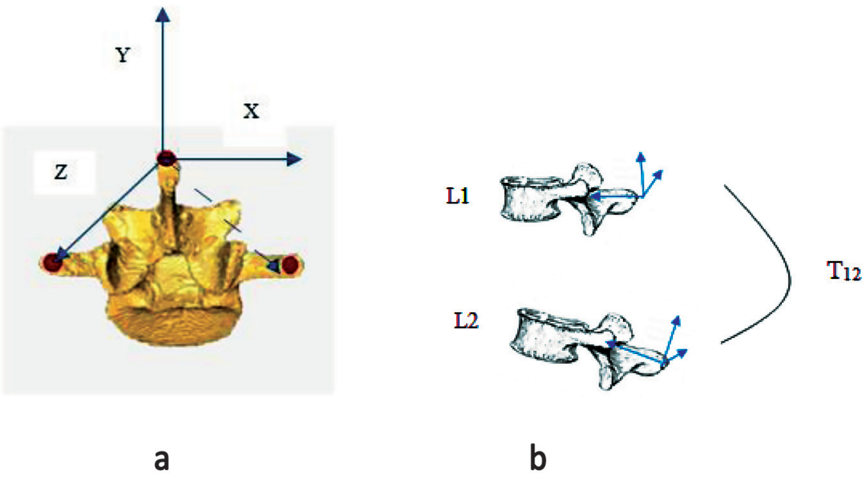

Figure 3. (a) the local coordinate system for one vertebra (b) intervertebral transformation between two consecutive vertebrae.

At first, a translation was applied to align the centers of the two coordinate systems and, then, a rotation was applied to register their axes (Fig. 4).

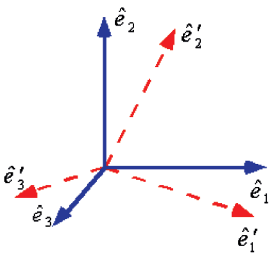

Figure 4. two concentric coordinate systems.

The rigid body rotation was calculated using the following equations [15].

Consider two systems $X \equiv \{e_1, e_2, e_3\}$ and $X' \equiv \{e_1', e_2', e_3'\}$. We are interested in obtaining the relation between $\{e_1'\}$ in X' to $\{e_1\}$ in X using a rigid body rotation.

$$\hat{e}_i' = Q\,\hat{e}_i = Q_{mi}\,\hat{e}_m \quad (1)$$

$$\begin{aligned} e_1 &= Q_{11}\hat{e}_1 + Q_{21}\hat{e}_2 + Q_{31}\hat{e}_3 \\ e_2 &= Q_{12}\hat{e}_1 + Q_{22}\hat{e}_2 + Q_{32}\hat{e}_3 \\ e_3 &= Q_{13}\hat{e}_1 + Q_{23}\hat{e}_2 + Q_{33}\hat{e}_3 \end{aligned} \quad (2)$$

$$Q_{ij} = \cos(\hat{e}_i, \hat{e}_j) = \hat{e}_i . \hat{e}_j \quad (3)$$

The local coordinate system for each vertebra relative to its neighboring vertebra before and after deformation is shown in Fig. 5a, 5b.

The physical space and CT images are roughly registered at first in order to have a single global coordinate system for both spaces. The first vertebra in physical space is registered to the first vertebra in CT space. Then, by knowing the local coordinate systems in the physical space and the intervertebral transformations in the 3D model from CT images, the consecutive vertebrae are registered by applying these intervertebral transformations to the local coordinate systems from the physical space.

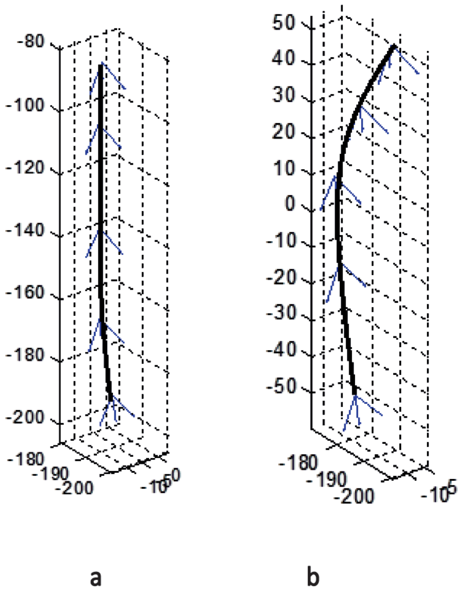

Figure 5. (a), (b) local coordinate systems for lumbar vertebrae before and after deformation (all measures are in mm).

$$L_{1ph}' = \tau L_{1ph}$$
$$L_{4ph}' = T_{34} L_3' \qquad L_{3ph}' = T_{23} L_{2ph}' \qquad L_{2ph}' = T_{12} L_{1ph}'$$
$$L_{5ph}' = T_{45} L_4' \quad (4)$$

$$\begin{aligned} L_2' &= T_{12} \times \tau L_{1ph} \\ L_3' &= T_{23} \times T_{12} \times \tau L_{1ph} \\ L_4' &= T_{34} \times T_{23} \times T_{12} \times \tau L_{1ph} \\ L_5' &= T_{45} \times T_{34} \times T_{23} \times T_{12} \times \tau L_{1ph} \end{aligned} \quad (5)$$

2.3. Registration Using Surface Based Method

In this method, surface points are collected from the vertebra in physical space and are registered with the 3D model from CT images. Firstly, a rough alignment is carried out by applying a point based registration algorithm (Arun's method [16]) to 4 corresponding anatomical landmarks on the vertebra in the 3D model CT images. This transformation is applied to all of the selected surface points from the physical space in order to align them with 3D model and, then, a surface based registration algorithm (ICP) is used in order to obtain a fine registration.

2.4. Validation

To obtain an optimal registration to validate the registration accuracy of the proposed method, CT compatible markers were placed over anatomical landmarks on each lumbar vertebra (Fig. 6a). The marker's unique design makes it easy to access its center in both CT images and real space to increase the accuracy (Fig. 6b, 6c). The markers were placed over anatomical landmarks on the posterior surface of the vertebra including the tip of the spinous process, the left and right transverse processes, the left and right superior and inferior articular processes and the junctions of the lamina and the side of the spinous process.

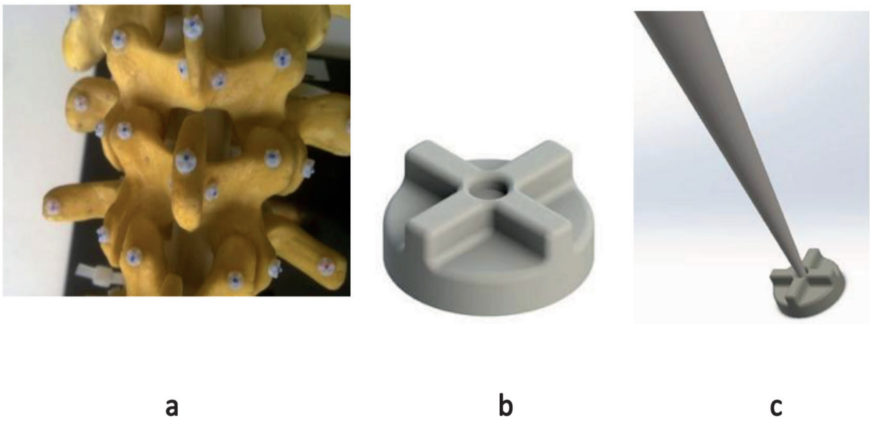

Figure 6. (a), (b) marker and tool tip's 3D appearance (c) CT compatible markers placed over anatomical landmarks.

The exact locations of these markers were acquired on the phantom using a tracked probe and also on the 3D model reconstructed from CT images. The optimal transformation was obtained by matching the known corresponding points in both spaces (3D model and phantom physical space). The registration was performed using Arun's point based registration algorithm [16]. The deviation from this optimal alignment can be calculated to quantify the registration accuracy of the proposed method.

2.5. Target Registration Error

The most important and clinically relevant measure is the target registration error (TRE). The TRE is defined as the distance between the image and physical targets' locations after registration. Target registration error is a registration error at some point of interest which is not used in the registration. TRE for one vertebra is defined in equation 6.

$$TRE(x) = \tau(x) - y \qquad (6)$$

Where x and y are the corresponding target locations in physical and image space respectively and τ is the transformation obtained from registering the two point sets.

The TRE for the entire section of the spine is defined by equation 7.

$$TRE_{total} = 1/N\sum_{t=1}^{N} TRE_i \qquad (7)$$

Where N is the number of vertebra used in registration and TRE i is the TRE of the ith vertebra.

Target registration error (TRE) was used to measure the misalignment in corresponding points after registration. Since this study was mainly focused on the accuracy of registration in pedicle screw placement, the target was considered the pedicle of the vertebra. For measuring TRE, a fiducial was placed on the pedicle (Fig. 7).

Figure 7. Location of the fiducial indicating the specified target.

3. Results

The results for the registration of vertebra L1 to L5 in preoperative CT images and intra-operative physical space using the highest performance method (point based registration) and the proposed method are indicated in table 1. The results are also compared to those of the surface based registration method using iterative closets point (ICP) algorithm [17] which was applied using 20 random points gathered from the posterior surface of the vertebra.

Table 1. Registration error (mm) using the proposed method, point based registration method (highest performance) and surface based method.

Vertebra \ Registration method	RMS (root mean square) registration error using point based registration	RMS registration error using the articulated model	RMS registration error using surface based registration (ICP algorithm)
L1	0.51	0.69	1.23
L2	0.59	0.77	1.19
L3	0.75	1.16	1.37
L4	0.86	1.21	1.89
L5	0.56	1.72	1.21
Total TRE	0.65	1.11	1.38

4. Discussion

We proposed an efficient framework for the registration of lumbar spine in pre-operative CT images and intra-operative physical space. The articulated model for spine was used to calculate the deformation between two postures of the spine. Having information concerning the two postures, the CT images can be updated according to the physical space any time during the surgery.

Since the exact location of corresponding points in the 3D model and the physical space are not distinguishable, after the initial alignment using approximate corresponding points, a surface based registration is required to improve the registration accuracy. This requires gathering points in the physical space of each individual vertebra and registering them with the 3D model reconstructed from pre-operative CT images. The proposed method decreases the registration time by eliminating the need to acquire surface points on each individual vertebra. It is also applicable in situations with defected vertebrae where anatomical landmarks are difficult to distinguish. In this case, the defective vertebra can be registered more conveniently by registering the adjacent vertebra and having knowledge about the inter-vertebral relations.

However, the accumulation of the errors caused by the multiplication of inter-vertebral transformations can decrease the registration accuracy in this proposed method.

Table 1 shows the results for registration using the point based method (highest performance method), the proposed method and the surface based method. Due to efficient use of the information from intervertebral transformation, this method reduces the tedious and time consuming task of surface point acquisition and also results in a 19.5 % decrease in total TRE compared with the surface based method.

The ultimate aim of this study was to provide a real-time registration of the preoperative images to intra-operative patient position in image guided spine surgery. The current surface based methods usually register each vertebra separately by collecting surface points on each vertebra. The proposed method used the intervertebral relations in order to avoid the surface point selection on each vertebra.

5. Conclusion

This study includes the information from intervertebral transformation of consecutive vertebrae, for the registration of preoperative images and intra-operative physical space of the spine for IGSS in navigation systems. Our preliminary results, carried out on a spine phantom indicate that this method is comparable with the commonly used surface based registration method.

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