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Coupling 2D/3D registration method and statistical model to perform 3D reconstruction from partial x-rays images data

T. Cresson, R. Chav, D. Branchaud, L. Humbert, B. Godbout, B. Aubert, W. Skalli and J.A. De Guise

Abstract— **3D reconstructions of the spine from a frontal and sagittal radiographs is extremely challenging. The overlying features of soft tissues and air cavities interfere with image processing. It is also difficult to obtain information that is accurate enough to reconstruct complete 3D models. To overcome these problems, the proposed method efficiently combines the partial information contained in two images from a patient with a statistical 3D spine model generated from a database of scoliotic patients. The algorithm operates through two simultaneous iterating processes. The first one generates a personalized vertebra model using a 2D/3D registration process with bone boundaries extracted from radiographs, while the other one infers the position and the shape of other vertebrae from the current estimation of the registration process using a statistical 3D model. Experimental evaluations have shown good performances of the proposed approach in terms of accuracy and robustness when compared to CT-scan.**

I. INTRODUCTION

Understanding the 3D nature of bone deformities in complex bone structures such as the spine is essential in improving the quality of diagnosis in preoperative planning [1]. For pathologies in spinal deformities such as idiopathic scoliosis, personalized geometrical models can be used to take into account patient-specific features and personalize the treatment to each patient. Several studies based on biplanar radiography are foreseen as an alternative to Magnetic Resonance Imaging (MRI) and Computerized Tomography (CT) in 3D reconstruction applications. The main advantages of using this technology are to avoid exposition of the patient to high levels of radiations, reduce the acquisition time and lower the cost of treatments. Moreover, for the clinical assessment of spinal deformities, the natural standing position is essential. However, this technique has to cope with some limitations induced by the imaging system when applied to anatomical structures such as the spine. Fig.1 clearly reveals some of these limitations. The main limitations are:

- 1) *Nature of the digitized signal*: In x-ray imaging, a compromise must be met between a patient's radiation exposure and the image noise level. The resulting noise level may become significant. At low radiation doses, there is often a high variation in brightness and contrast across the different vertebral levels.
- 2) *Region of data acquisition*: It is common to observe vertebrae that are partially or completely hidden because of soft tissues, air cavities and/or others structures that are superposed and interfere with a good visibility of the spine. As a result, the visible landmarks on some vertebrae can vary considerably. Hence, the vertebrae of the upper thorax are usually hard to identify clearly (see Fig.1).
- 3) *Nature of the bone structure*: Due to projectional parallax effects, the shape and appearance of the vertebrae are more complex than what is observed in classical images such as CT or MRI. In standard x-ray images, the visual interpretation of the various individual bone segments of the spine remains problematic.

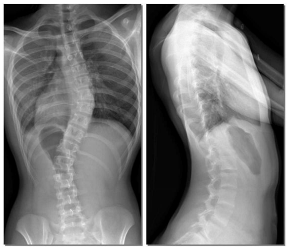
Fig. 1. Example of a radiograph pair from the same patient showing a postero-anterior view (left panel) and a lateral view (right panel). Due to poor visibility, some vertebrae may appear fused.

Therefore, the quality of all vertebral segmentation results from x-ray images and the accuracy of the 2D/3D registration between an anatomical template model and the segmentation results are the two key points forming the bases of the 3D reconstruction process. However, as a consequence of some limitations, segmentation of vertebrae contours can never be completely free of biases and artifacts. It is common to have regions without information, sometimes covering up to several vertebrae. Classical 2D/3D registration algorithms assume that the structure of interest is completely visible. While acknowledging the difficulty of obtaining a faithful and complete description of the objects, the underlying idea developed in this work is to overcome these difficulties through the exploitation of relevant information contained in x-ray images to infer location and shape of any obscured portions of the spine. This offers the highest possible reconstruction accuracy in noisy and boundary-free images. The algorithm alternates iterations of two interacting processes. The first one generates a personalized model of a partial or complete vertebra using a robust 2D/3D registration process with boundary edges extracted from radiographs. The second one refines the reconstruction of all portions of the spine untreated by image processing based on current estimations of some anatomical structures by registration using a statistical

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T. Cresson, R. Chav, D. Branchaud, B. Godbout and J.A. De Guise are with the ÉTS and the LIO, CRCHUM, CANADA (e-mail : `lio@etsmtl.ca`)

L. Humbert, B. Aubert and W. Skalli are with the ENSAM and the LBM, UMR CNRS 8005, FRANCE

model developed in [2]. Finally, all portions of the spine with unreliable boundary edges are inferred from portions of the registered spine.

Before explaining the proposed method based on the adaptation and/or improvement of widely used techniques (section III, IV, V), the following section gives an overview of the related work for the reconstruction of the spine. In section VI, experimental evaluation shows good performances for the proposed approach in terms of accuracy and robustness when compared to those CT-scans.

II. RELATED WORK

Some studies proposed for the 3D reconstruction of the spine rely on the manual identification of anatomical landmarks on each vertebra in both the frontal and sagittal radiographs. The reconstructed landmarks are then used to deform generic vertebral templates (e.g. polygonal meshes) in order to obtain a realistic visual representation of the spine [3]. However in order to improve the 2D localization accuracy for some poor visibility landmarks, studies were conducted to propose more automated approaches using statistical shape methods. Thus [4] only estimates manually reliable landmarks that are easy to identify in x-ray images. A prior knowledge of the spine, encoded in a statistical articulated mode, is used to find the orientation and the shape of the other vertebrae. However it is difficult to precisely identify, even in good quality images, low-level primitives such as exact landmark positions. In [5], the silhouettes of all vertebral models are projected in the frontal and sagittal images and may be adjusted by the operator to directly translate and rotate the 3D models. Interpolation and optimization steps are then used to infer vertebrae that are not adjusted by the operator. Humbert *et al.* [2] propose to extend the approach of [6] based on relationships between geometric descriptors of a given vertebra by using linear regressions of the whole spine by relying on relationships between geometric descriptors of one vertebra in regard to another one. This approach allows vertebrae model deformation to obtain the detailed 3D morphology of vertebrae. All theses techniques require significant operator intervention to adjust the silhouette of all vertebral models in the x-ray images. Performing this task manually is extremely time consuming, tedious and error-prone. Benameur *et al.*[7] and Kadoury *et al.*[8] propose to accomplish this task by using an automated method to enhance the reproducibility of the reconstruction method. Benameur *et al.*[7] applies point distribution models to reconstruct a geometric hierarchical model containing the typical deformation modes, in both the whole spine and individual vertebra geometric structure. The reconstruction method first consists in fitting the projections of the deformable template of the whole spine and then in fitting each vertebra with segmented contours in the two x-ray radiographic projections. Kadoury *et al.*[8] proposes an approach combining statistical 3D models of the spine and image processing. The statistical model of [8], based on an algorithm derived from a locally linear embedding transformation, allows the generation of a crude statistical 3D model from the 3D spinal curve of the personalized spine. Then, this model is subsequently refined by adjusting the 3D vertebral coordinates. In contrast with the method proposed here, these two solutions do not consider the *a priori* informations in the registration of each vertebra during the refinement step to enhance the statistical solution in untreated portions of the spine. Hence, in [7] when the initialization of the whole spine fails to adequately fit unseen objects deviating too much from the training set, the statistical solution is not enhanced in portions where there is no registration. In addition, in [8], the first solution does not use any information of vertebrae extracted from x-ray images.

III. STATISTICAL AND GEOMETRICAL MODEL

A. Construction of parametric spine model

We use the statistical and geometrical model of the spine proposed by Humbert *et al.* [2]. In this technique, the parametric spine model is based on *a priori* hierarchical knowledge on the anatomic structure.

Global parametric model - spine: A 3D spinal curve and a parametric model built from an *in vivo* database of 175 subjects of the whole spine (91 asymptomatic, 47 moderate and 37 severe idiopathic scoliosis) are used. Estimated parameters are: depth, width and position of the two endplates along the spinal curve. In addition to statistical inference, smoothing constraints on the spinal curve ensure a geometrical continuity in terms of vertebral rotations. The descriptors of this parametric model are statistically linked together using a multiple linear regression technique to obtain a "longitudinal" inference.

Local parametric model - vertebra: A morphological database of dry, normal and scoliotic vertebrae is constructed from direct measurements of 1628 dry isolated vertebrae [6]. Eight specific measurements of the vertebral body dimensions and 21 anatomical 3D points were extracted to define the basic vertebral shape. The vertebral body-dimension parameters included in the database are: anterior, posterior, left, right vertebral body height plus width and depth of upper and lower vertebral endplates. The descriptors of this parametric model are statistically linked together using a multiple linear regression technique to obtain a "transversal" inference.

B. 3D reconstruction process

The reconstruction process combines global and local parameters into hierarchical statistical model to develop a method that infers vertebral location and shape from other structures imbedded in noisy images. Upon the displacement of any of the control points in the global parametric model, the other descriptor parameters are statistically re-estimated using "longitudinal" inference. Modifying one or all of the descriptor parameters leads to a re-estimation of the eight variables of the local parametric model. The global and the local parametric models are linked together by these eight measurements which are a subset of all the available measurements on the local parametric model. Modifiying any of these eight vertebral descriptor parameters in the global parametric model leads to a statistical re-estimation of the 21 3D coordinates for each local vertebra model based on "transversal" inference. Finally, a highly detailed 2000-points model is generated from the 21 anatomical landmarks using a surface interpolation algorithm.

C. Multiple linear regression

Estimation of unknown parameters (descriptor parameters not estimated by image processing) based on known parameters (descriptor parameters estimated by registration) of the global and local parametric models can be obtained via a classical multiple linear regression. However, we rely on partial least squares regression (PLSR) to build predictive models for high-dimensional regressors and one, or several, response variables. Furthermore, the PLSR approach leads to stable, correct and highly predictive models even for correlated variables. The goal of a PLSR is to build a linear model, $\mathbf{Y} = \mathbf{X}\beta + \epsilon$, to predict variable responses (independent variables) $\mathbf{Y}$ from regressors (dependent variables) $\mathbf{X}$ where β is a regression vector of coefficients and ϵ is the error term for the model. Specifically, PLSR searches for a set of components (called *latent* vectors) that performs a simultaneous decomposition of $\mathbf{X}$ and $\mathbf{Y}$ under the constraint that these components explain as much as possible of the covariance between $\mathbf{X}$ and $\mathbf{Y}$. This step generalizes principal component analysis. It is followed by a regression step where the decomposition of $\mathbf{X}$ is used to predict $\mathbf{Y}$. Regressing the dependent variable $\mathbf{Y}$ on this set of latent variables is more stable.

IV. 2D/3D REGISTRATION OF ONE VERTEBRA

For the registration of each vertebral model in frontal and sagittal x-ray images, we use a variant of the well-known iterative closest point algorithm (ICP) [9]. The main difference with the original version of the ICP algorithm is that for the problem of the pose estimation we include a metric based on a robust norm - we retain the Tukey M-estimator - rather than the classical quadratic error metric. This solution simply turns out to be an Iterative Reweighted Least Squares (IRLS) optimization [10]. It enhances the robustness of the registration process in terms of false correspondences due to segmentation errors. The proposed algorithm consists in alternating between two separate problems:

- Repeat until convergence:
  - Matching phase: determine correspondences between features extracted from x-ray images and from the 3D model of the vertebra. The segmentation problems are not discussed in this paper due to the extended literature on the subject.
  - Pose estimation phase: estimating the optimal rigid-body transformation using these correspondences and the IRLS optimization.

The convergence criterion is based on tracking the evolution of the global residue χ, defined as the square root of Chi-2. The definition of a minimal relative gain μ enables introduction of the stopping criterion $|\Delta\chi| < \mu\chi$. Applied to the vertebral body, this method only adjusts the vertebral position and scale. In order to deform the vertebral body and adjust its shape, we use a hierarchical data structure of the anatomical model which relies on the decomposition of the vertebral body and pedicles in eight entities: anterior, posterior, left, right vertebral body walls and inferior, superior endplates and two pedicles. After the registration of a complete vertebra, we apply once more the same process to each of its sub-elements described above, hence locally deforming the vertebral model.

V. 3D RECONSTRUCTION OF THE SPINE

In order to recover the whole spinal shape from sparse data, we rely on good signal/noise ratio (SNR) areas in radiographs for the process of 2D/3D registration and infer from them the others parts of the spine model. The proposed algorithm combines a robust ICP algorithm (see IV) with a parametric spine model (see III):

- Do for each vertebra:
  - 2D/3D registration: estimate, for a given vertebra, the optimal values of the parameters from the hierarchical data structure (position and shape).
  - Self improvement of the spine model: estimate the whole set of descriptors of the parametric spine model using longitudinal and transversal inference based on the updated values of the descriptor parameters of the registered vertebrae.

The selection criterion to determine which vertebra should be processed and in which order depends on the quality of the segmentation. For each vertebra, we estimate a cost function which depends on the value of the gradient norm and the number of selected pixels resulting from the segmentation process. The value of the cost function is higher when the morphology of the cloud of pixels is closer to the mean statistical shape of the vertebra model. If the value is smaller than a threshold, the vertebra is not registered but only estimated by the parametric spine model using longitudinal and transversal inference.

As it is the case for the other ICP methods, the registration process also relies on a local optimization method, which does not guarantee convergence to the global minimum, due to its reliance on the initialization. In addition to the fact that our approach provides a reliable reconstruction of the spine from sparse data, the result of dynamically re-estimating the vertebral positions and the shapes from the parametric spine model allows a faster convergence towards the final solution and avoids several local minima.

VI. RESULTS AND DISCUSSION

Some results on shape accuracy and inter observer shape variability based on 20 lumbar vertebrae (L1 to L4) from 8 patients of the Erasme Hospital (Belgium) are presented here. 3D reconstructions of theses structures are obtained from a low-dose digital radiographic system EOS$^{\text{TM}}$ (biospace med, France) using the proposed method. We compare these reconstructions to 3D surface models of vertebral shapes reconstructed from CT-scan. The validation process is limited to the regions of the vertebral body and pedicles; the

TABLE I

STATISTICAL ANALYSIS OF THE SHAPE ACCURACY ERRORS: POINT-TO-SURFACE DISTANCES FOR VERTEBRAL BODY AND PEDICLES EVALUATED BETWEEN 3D RECONSTRUCTIONS FROM BIPLANAR X-RAYS AND FROM CT-SCANS (MEAN±STD DEVIATION IN MM).

	L1	L2	L3	L4
N	3	4	6	7
User 1	0.94 ± 0.84	0.86 ± 0.85	0.89 ± 0.88	0.93 ± 0.89
User 2	0.84 ± 0.81	0.87 ± 0.78	0.84 ± 0.76	1.00 ± 0.93
User 3	0.67 ± 0.53	0.73 ± 0.56	0.91 ± 0.75	0.96 ± 0.78

proposed method is designed to handle only those regions. The validation step consists in fitting the two corresponding models and calculating point-to-surface distances for the two regions.

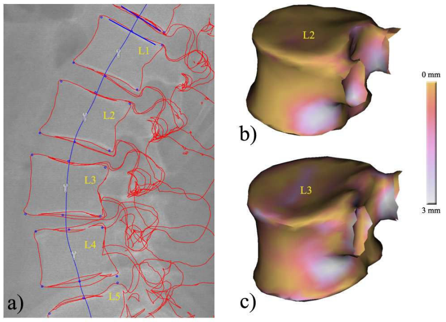

Fig. 2. (a) Projection of the silhouette of the 3D reconstruction of vertebrae (L1 to L5) on a sagittal radiograph of a patient. Reconstruction for L2 (b) and for L3 (c) lumbar vertebra with the distance map of the surface error superposed on the reconstructed model.

Three users, familiar with the reconstruction software, performed the 3D reconstruction procedure. Each user is asked to identify a curve on both radiographs passing through the vertebral endplates centers to generate the corresponding 3D spinal curve. Furthermore, T1 upper endplate and L5 lower endplate on both radiographs are identified. Finally, the positions and the shapes of the spine model components are adjusted on the patient-specific structure with the proposed algorithm. Fig.2.a shows results with the projections of the silhouette of deformed 3D vertebra contours fitting adequately the bony edges of the corresponding vertebra in the sagittal radiographic image.

Table 1 summarizes for the three users, the statistical error analysis for the shape accuracy for 20 vertebrae data set (vertebral body and pedicles). The *in-vivo* experiments show an average and a standard deviation error of less than 1.0 mm for the 20 vertebral shapes reconstructed by the three users. For the inter observer variability, we obtain a small average error of 0.5±0.8 mm (mean±2×STD) for the 20 shape vertebrae. These accuracy and precision evaluations demonstrate good performances of the proposed method in terms of accuracy and robustness. As for the point-to-surface mappings between the reconstructed model from CT-scan and the reconstructed model from the proposed method for a L2 and L3 lumbar vertebra, the b and c panels in Figure.2 show that the largest errors are generally located in pedicle areas and behind the vertebral body. This is not surprising because the registration in the proposed method only fixes the position of pedicles, not their shapes. A more accurate spinal reconstruction can be obtained with a refining combining the proposed method and an elastic deformation technique such as the kriging algorithm in a coarse-to-fine multi-scale approach. Compared to the method proposed in this study, the reconstruction method proposed in [2] has a similar shape accuracy evaluation for an average error of less than 1.0 mm in the vertebral body and pedicles regions, it is however time-consuming, requiring about 8 minutes for the whole spine. The integration of image processing techniques with the parametric spine model saves time and a considerable amount of human intervention. The proposed method requires only 3 minutes to complete, allowing an acceptable 3D reconstruction and fast enough for a routine clinical use.

VII. CONCLUSIONS AND FUTURE WORKS

We have presented an efficient solution for the 3D reconstruction of the spine from two x-ray images using a method which combines statistical inference and image processing approaches. Experimental results confirm that the proposed method gives viable 3D reconstructions and is an accurate and reliable alternative to competitive state-of-the-art methods. Further work will consist in testing more cases to confirm the quality and the robustness of this technique and its accuracy to digitize complete spine from a limited number of vertebrae.

VIII. ACKNOWLEDGMENTS

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