Prediction of the 3D Spinal Alignment from External Shape of the Back in AIS Patients Using Regression Model

Stefano Caturano
Department of Basic and Applied Engineering Sciences
Sapienza University of Rome
Rome, Italy
caturano.1754345@studenti.uniroma1.it

Mirko Kaiser
Institute for Biomechanics, Laboratory for Movement Biomechanics
ETH Zurich
Zurich, Switzerland
mirko.kaiser@hest.ethz.ch

Martin Bertsch
Institute for Human Centred Engineering – Biomedical Eng. Lab
Bern University of Applied Sciences
Biel, Switzerland
martin.bertsch@bfh.ch

Tito Bassani
IRCCS Istituto Ortopedico Galeazzi Laboratory of Biological Structures Mechanics (LABS)
Milan, Italy
tito.bassani@grupposandonato.it

William R. Taylor
Institute for Biomechanics, Laboratory for Movement Biomechanics
ETH Zurich
Zurich, Switzerland
bt@ethz.ch

Saša Ćuković
Institute for Biomechanics, Laboratory for Movement Biomechanics
ETH Zurich
Zurich, Switzerland
sasa.cukovic@hest.ethz.ch

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***Abstract*— One of the most challenging tasks in non-invasive diagnosis of Adolescent Idiopathic Scoliosis (AIS) is to find the correlation between internal spinal deformity and external shape of the back and to create a model to predict internal curve from 3D scans of the back surfaces only. Consequently, X-ray imaging and analysis could be potentially reduced which lead to decreased cumulative dose to the patient and the risk for malignancy development later in life. We proposed a regression model that considers correlation between 3D coordinates of the ground-truth internal spinal curve and 3D coordinates of external asymmetry curve to predict internal spinal alignment close to the real one. With a limited number of samples used to create it, this model is able to provide an acceptable approximation of the spinal internal alignment particularly in sagittal plane, with a mean 3D displacement between predicted and real curve of around 10-12 mm. Quality of prediction could be significantly improved by simultaneously acquiring 3D scans of the back surface and X-ray scans of the patient, and adding to the model external features like scapulae or rib cage which are future steps towards improvement and clinical validation.**

Keywords—Idiopathic Scoliosis, Optical Diagnosis, ScolioSIM, Patient-specific 3D Models, Spinal Alignment

I. INTRODUCTION

Scoliosis is a complex deformity of the spine that affects 0.47–5.20% of the global population [1] from which 2 to 4% belong to idiopathic scoliosis, and almost 80-90% belong to Adolescent Idiopathic Scoliosis (AIS) [2]. AIS type of scoliosis is developed by unknown etiology and occurs mainly during preadolescence or before skeletal growth and maturation and mostly affects female subjects. AIS is mainly manifested as a frontal and lateral distortion and deformity of the spine which includes 3D axial rotation of vertebrae that affects the shape of rib cage (thorax) as well as position of scapulae and pelvis and consequently aesthetic appearance of patient's body and posture.

If remained untreated or lately detected, AIS can lead to severe physical changes of the affected patients and to secondary symptoms such as chronic pain, irreversible pulmonary and heart dysfunctions [3], etc. Moreover, overall morphological imbalance of the trunk can cause frustration, avoidance, low self-esteem and other unhealthy psychological states of the patient [4]. Thus, it is of a crucial importance to detect AIS in the early stage and to treat it properly in order to reduce the deformity, stop further progression, and maintain lung and heart function, as well as to increase quality of life of patients and to prevent further clinical costs.

Traditionally, scoliosis is detected through preliminary visual inspections of the patient's trunk and dorsal surface in which case undesirable asymmetries could be detected. To approve their findings, clinicians rely on one AP/PA or biplanar upright X-ray images from which internal indicators and curvature segments of the deformity could be evaluated [5]. In general, scoliosis is defined as a deformation of the spine by an angle of more than 10º in the coronal plane, measured on standing radiographs, using the Cobb technique [6]. Here, clinician manually detects segments of the curves and measures primary (the biggest) and secondary angles of AIS deformity curve. Fig. 1 illustrates Cobb angle (CA) measures over biplanar radiography images and external dorsal surface of the same AIS patient.

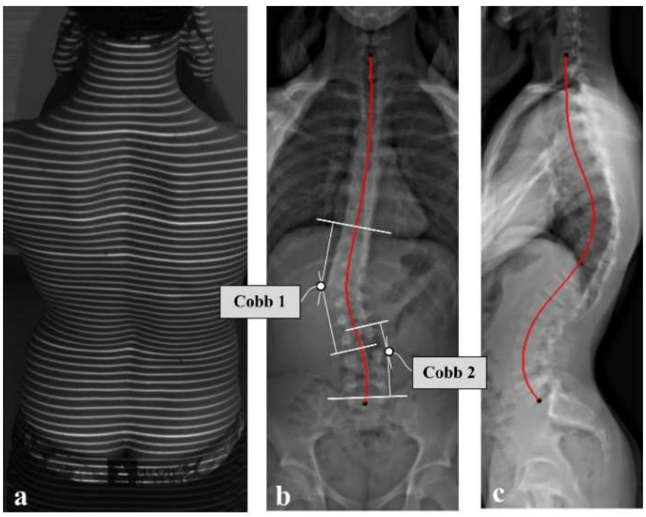


Fig. 1. AIS case: a) back surface of the male adolescent patient in optical scanning procedure, b) frontal X-ray image with two CAs of the primary and secondary curves of the frontal alignment, c) sagittal plane with sagittal spinal alignment

It is obvious that the biggest CA on X-ray image will have the most influence on the dorsal surface deformation and its shape, but this technique has high intra- and interobserver variability, neglects other anatomical elements and requires highly trained observers [7].

Additionally, the main drawback of traditional radiographic methods in AIS assessment is their harmful effect on the young population, especially due to multiple radiation exposures while monitoring progression of the disease, which increases the risk for malignancy development later in life [2], [8]. Other tests e.g. Adam's forward bending test in combination with scoliometer can estimate the value of CA by avoiding the X-ray imaging, but it neglects other aspects of AIS such as pelvic tilt, shoulder discrepancies, etc.

Recently, new nonionizing and highly precise methods are introduced and clinically implemented, particularly technologies that involve marker-based 3D optical systems have been considered as alternatives to X-ray imaging (e.g., Vicon, Moirè Topography, Quantec Spinal Imaging System, Integrated Shape Imaging System) due to their ability to digitalize dorsal surface and to produce a non-invasive estimation of the external back profile [9], [10]. They allow calculation of external parameters of AIS [11] and consequently reducing exposure to X-ray ionizing radiation. Another 3D optical approach, for example rasterstereography (RST), is a less expensive, non-ionizing technique which estimates deformity-related changes of the patient's back with only light as a medium by projecting horizontal stripes on patient's back (Fig. 1a), thus allowing better insights and investigation of external shape and its contours [12]. However, none of the current solutions visualize the 3D model of the patient-specific spine and its structure in real time, statically or dynamically.

A novel technical solution for scoliosis simulation called ScolioSIM, based on Computer Aided Design (CAD) model and numerical simulation modules of CATIA v5 was recently developed [13]. This tool aims to generate an advanced 3D model of a patient-specific spine and to extract internal deformity parameters from an external 3D surface in habitual upright posture only. It identifies end vertebrae of the primary and secondary curve of AIS, localizes the apex vertebra or disc, and calculates and compares over 100 deformity metrics (both external and internal), including sagittal and frontal CA and scoliosis society (SOSORT) recommended angles, vertebral and intervertebral transpositions and axial rotations, and various dorsal measurements. Improvements in linking external and internal biomechanical parameters are clearly required in terms of better prediction of internal spinal alignment from surface only, and validation against X-ray remains inadequate.

In this paper we describe some of previously collected and fused biplanar images with 3D optical scans of patients with AIS [14]. These datasets were processed with ScolioSIM and then we investigated the level of correlation of generated internal indicators with external shape with the primary focus on external asymmetry curve of the back (that passes through spinous processes – the most prominent elements of vertebrae palpable on the skin) and internal spinal alignment from the ground truth modality e.g. EOS biplanar radiographs. For this experiment, both 3D curves were drawn manually.

II. Materials and Methods

In this study we retrospectively analysed previously collected samples of 94 AIS patients. Included are 83 females and 11 males; mean age is 13.21±2.34 years, mean weight 49.04±10.34 kg, mean height 158.74±11.16 cm. As a standard of care, a regular clinical examination was conducted, and biplanar X-ray images were obtained using EOS device to evaluate the deformity and asymmetry curves. Additionally, a 3D optical and markerless scanning was performed to digitalize patient's back surface. As the surface topography represents a contactless, non-ionizing method, participants were not exposed to any specific risk [14].

Fig. 2 illustrates the 3D patient-specific model of the subject from Fig. 1 and its optical surface processed by the ScolioSIM tool, which is a part of ScolioMedIS information system previously developed [15], [16].

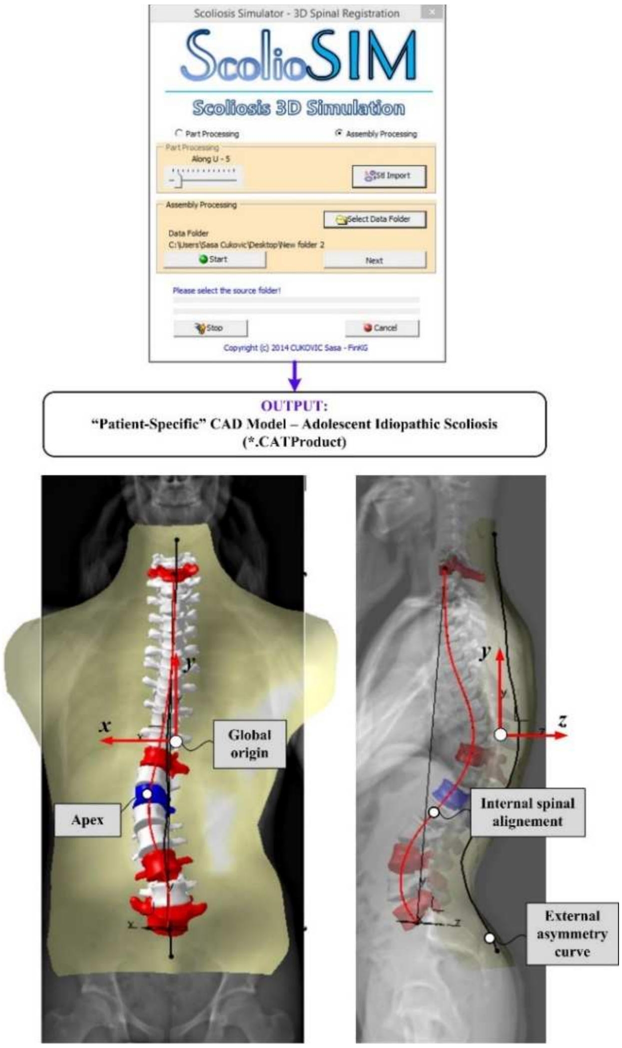


Fig. 2. Patient-specific 3D deformity model generated by the ScolioSIM tool for the subject illustrated in Fig. 1

A. *Recruitment of subjects*

AIS patients for this study were recruited according to the following criteria:

- Inclusion criteria: Age 8 years until skeletal maturity (approx. 16-18 years), males and females, diagnosis of adolescent idiopathic scoliosis - AIS (without any known bony deformity or neurogenic cause).
- Exclusion criteria: All non-idiopathic scoliosis: i.e., early onset (<8 years), syndrome-associated, neurological (cerebral palsy, syringomyelia, etc.) or with a bone deformity (e.g., hemi-vertebra), inability to follow the procedures of the study, e.g., due to

psychological disorders, dementia etc. of the participant, pregnant women.

B. *Datasets processing*

Ground-truth biplanar images were manually aligned (rigidly registered) towards 3D optical surfaces with respect to visible prominent points and two 2D spline-type curves were used to approximate internal spinal alignment (projection of the 3D curve that passes through centroids of intervertebral discs and vertebral bodies) from L5/S1 to C7 in frontal and sagittal planes.

Internal spinal alignment and asymmetry curve of dorsal surface, both described with 82 points, as well as key anatomical landmarks of the back were then input to ScolioSIM tool. Coordinates of vertebral centroids, main CAs, axial vertebral rotations and other deformity indicators were generated and processed with the main focus on investigating two main deformity curves (asymmetry/external and internal) and back shape, axial vertebral rotations and CAs.

C. *Data analysis*

In order to create a regression model that is able to predict the internal spinal alignment based on external shape (thus avoiding manual intervention over biplanar images), correlation between internal and external deformity curves has been calculated. Despite the fact that we had 94 samples for this investigation, we obtained acceptable regression model. However, more samples of moderate to severe AIS patients are being acquired to improve the quality of the model and statistical validation of the prediction.

In our study, 80 of the 94 samples have been used to fit the regression model, while other 14 have been used as validation (test) set. During training and testing procedures, different combinations of training and testing set sizes have been tried (50 vs. 44, 60 vs. 34, 70 vs. 24, 80 vs. 14 and 90 vs. 4). With the training set smaller than 80 samples, the model was not able to provide acceptable results, due to the large variability of scoliosis severity in available samples. With the test set composed by only 4 samples, it was not possible to have a good testing from a statistical point of view (cross-validation provided different results depending on the samples belonging to the test set). Finally, combination of 80 training samples and 14 test samples has been considered the best combination to train the model and to verify the quality of prediction in a proper way, since the cross-validation provided similar results in different cases. The results presented refer to 14 samples randomly selected.

Firstly, all 3D surfaces have been resampled in order to have the same number of points in belonging point clouds. Here a grid of 40x50 points has been used and for each point, the Z coordinate of the origin axis system (Fig. 2) has been calculated as a mean of the four nearest neighbours with respect to the original back surface (point cloud of a cca. 2000 points). Then, the Pearson correlation coefficient has been calculated for each correlation. In particular, the coordinates of each point of the internal spinal alignment have been correlated to the coordinates of each point of the external asymmetry curve and of the external surface, and for each relation coefficients of the linear regression have been calculated.

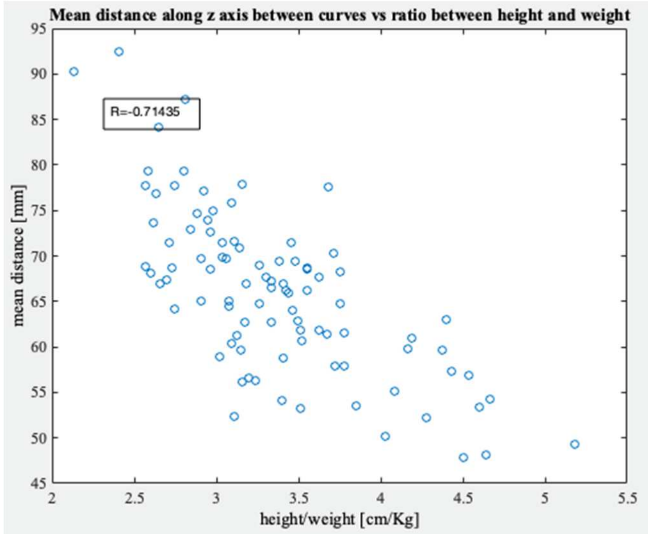
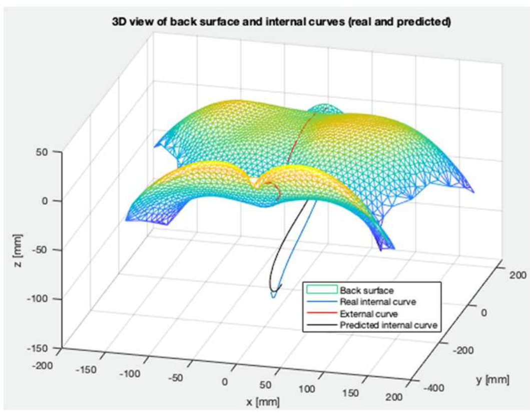


Fig. 3. Correlation between the ratio height/weight and the distance between internal and external curve in sagittal plane

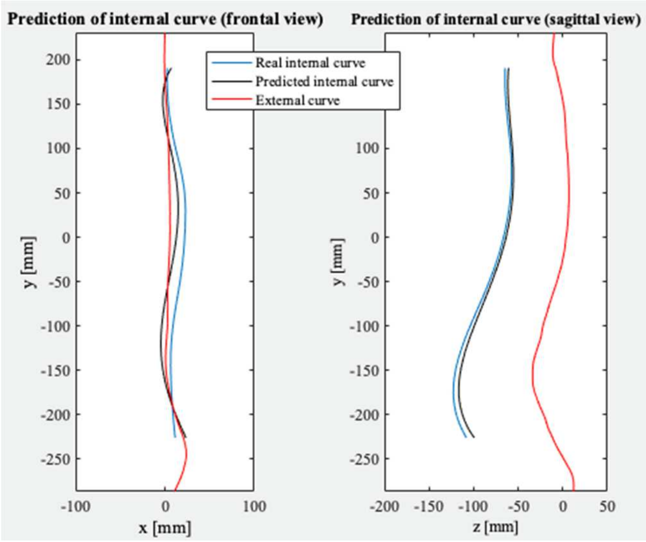
Once each internal point has its correlation values and coefficients of regression associated, the coordinates of the internal spinal alignment have been predicted starting from the external point that showed the higher values of correlation (R>0.9) with the ground-truth (internal) curve. As output of the predictive model, 3D coordinates of 82 points describing the internal spinal alignment can be evaluated and reliably interpolated with polynomial 3D curve of 5th degree. After the first prediction step, the distance between internal and external curves in sagittal plane (along Z axis) can be corrected using information about patient's height and weight. In fact, ratio between height and weight shows a significant correlation (Pearson corelation coefficient is R>0.7) with the mean distance between curves in sagittal plane (Fig. 3). Internal 3D curve is translated along Z axis in order to match the predicted value.

III. Results

The prediction model is tested on all 94 samples, and the error associated to the prediction is calculated both for all 94 samples and for 14 test samples alone. In Fig. 4, the result of the prediction for the first sample of the test set is presented. To assess the goodness of the prediction, the predicted internal spinal 3D curve is compared to the real internal spinal curve (created and combined over two ground-truth 2D biplanar images). In order to do this, the predicted curve is firstly resampled with the aim to be descripted by the same number of points (82) as of the ground truth curve.



a)



b)

Fig. 4. a) 3D back surface with external and internal curve (real and predicted), b) result of internal curve's prediction in frontal (left) and sagittal plane (right) for the same patient

Planar prediction error is calculated as the mean distance between the two 3D curves projected in frontal and sagittal planes (Fig. 4b), and also global error is calculated as mean distance between curves in 3D (Fig. 4a).

In Table 1, mean sagittal, frontal and global errors and associated standard deviations are reported for all and for the test samples before and after the correction with the height/weight ratio, while in Fig. 5 boxplots of mean error for test samples after correction are presented.

TABLE I. MEAN ERROR AND STANDARD DEVIATION

	All Samples		
	Frontal	***Sagittal***	***Global***
Before	7.28±3.40 mm	7.72±4.00 mm	11.91±4.53 mm
After	7.28±3.40 mm	6.83±3.34 mm	11.15±4.26 mm
	Test Samples		
	Frontal	***Sagittal***	***Global***
Before	7.90±3.66 mm	8.40±3.73 mm	13.17±4.32 mm
After	7.90±3.66 mm	8.01±4.28 mm	12.62±5.26 mm

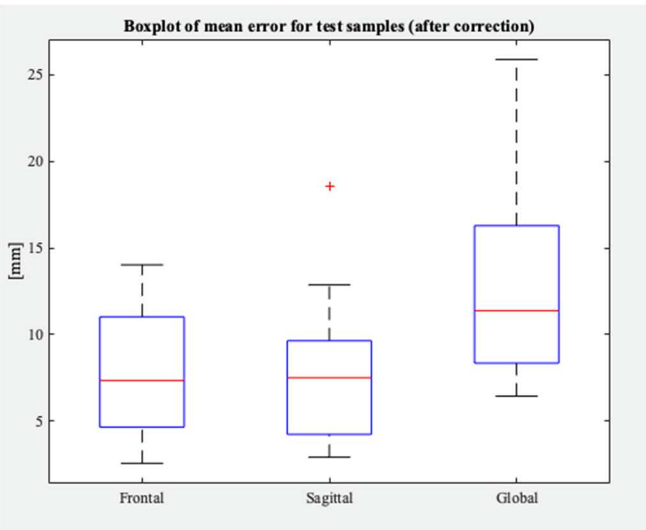


Fig. 5. Boxplot of the mean prediction error for test samples; from left to right: global error, error on frontal plane, error on sagittal plane

Despite the fact that the mean error is almost the same for frontal and sagittal plane, the prediction is more accurate for sagittal, where the curves closely follow the global shape of the spine (Fig. 6).

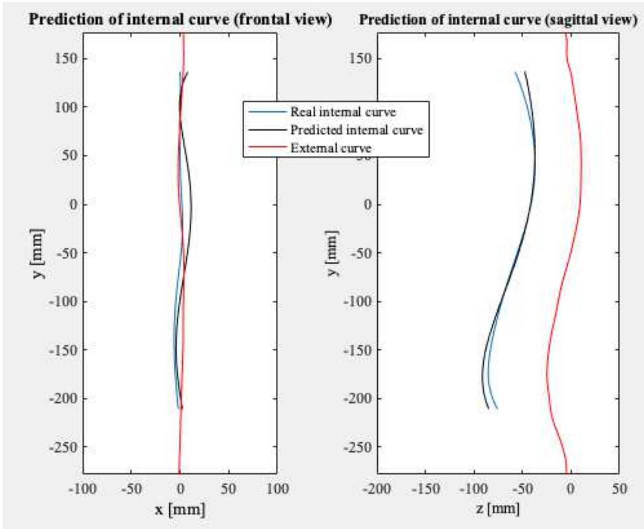


Fig. 6. Illustration of sgiital profile prediction for the random sample (no. 6) of test set

The global error is 11.15 ± 4.26 mm for all the samples, and 12.62 ± 5.26 mm for test samples, and it's comparable with results presented by Nerot et al. [17], [18], where the study focus was to predict coordinates of spinal joint centres from external back profile. The mean error changes for different segments of the spine, and in particular, it has higher values for thoracic region, while it decreases for lumbar and cervical segments (Fig. 7).

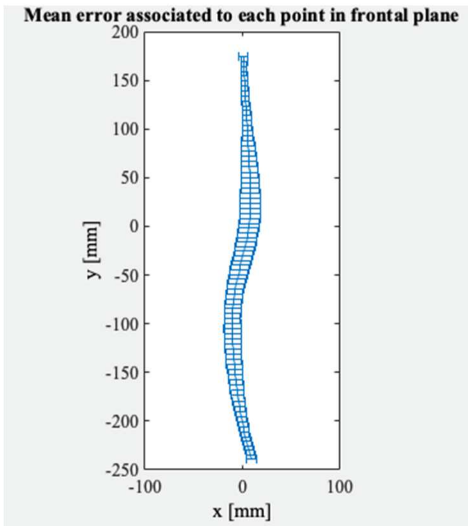


Fig. 7. Visualisation of the mean error's value for each point – it increases in thoracic and decreases in lumbar and cervical regions

Values of correlation and consequently prediction and all errors are influenced by the position of the patient in scanning process. Sometimes patient changes his posture between the two separate procedures. Namely, optical acquisition and X-ray radiography were not taken simultaneously, and when this happens the surface shape captured by the 3D scan does not match with the silhouette acquired from X-ray radiography (Fig.8).

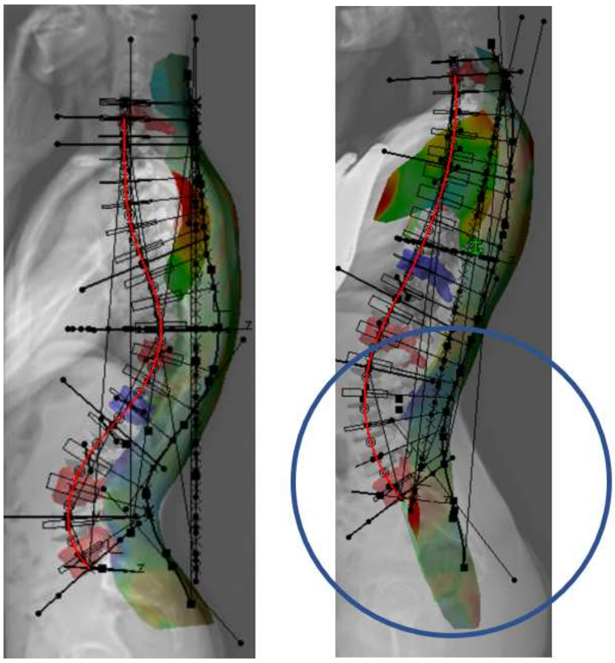


Fig. 8. Fusion of two modalities (X-ray and 3D optical surface): Perfect matching (left); Mismatched fusion due to changed posture of the subject in sagittal plane (right)

In our datasets 6 subjects showed unusual values of distance between internal and external curves in the sagittal plane, and particularly in the lumbar spinal region. They could be considered as outliers and by excluding them from training, correlations and predictions would be improved. However, they have been included in both training and testing procedures because of the limited dimension of the dataset, and since this error only affects the prediction in the sagittal plane. Fig. 9 shows higher error for a test sample belonging to the 6 outliers.

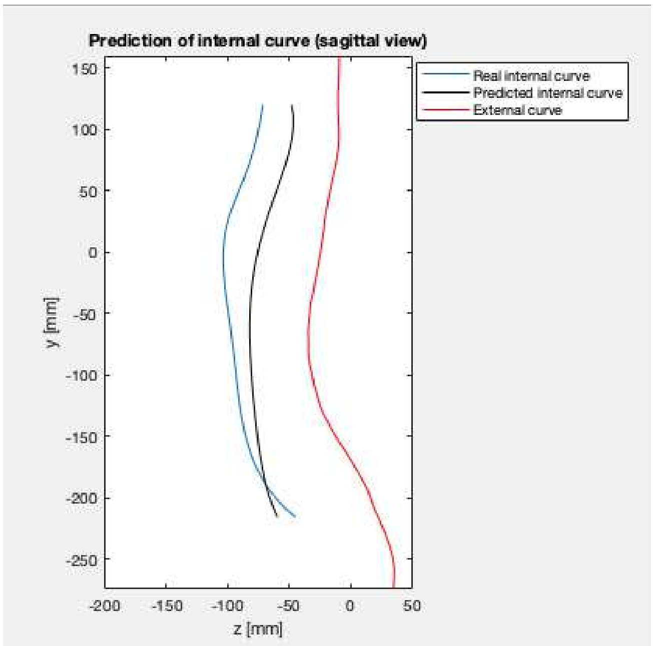


Fig. 9. Results of prediction in sagittal plane for one of the samples considered as outlier.

IV. Discussions

Predicting the shape of the spinal curve from 3D scans of the back surface is one of the most challenging tasks related to diagnosis of AIS, a common disease that affects often very young population. Finding a solution to describe the shape of the spinal alignment without exposing to X-ray would avoid the cumulative release of radiation dose to the patients, thereby not increasing the risk of cancer [8], especially in multiple repetitions during follow-up sessions. Different approaches have been proposed, from the finite element [19] to geometric models [17]. In this paper, we propose a prediction model obtained with a lower number of samples and it is nevertheless able to provide acceptable results. The goal of the model is to predict not only the position of critical points (e.g., centroids of vertebrae), but the whole spine by associating each point of the external curve to points on internal curve.

Results showed a mean global error between 11 to 12 mm which is comparable with previous studies on this issue [17], [18]. By analysing the distribution of the error, it is clear that it is not evenly distributed along the spine, with higher values for the thoracic region (Fig. 6). This suggests to additionally investigate the correlation between thoracic region and some anatomical features that have not been considered during this study, such as rib cage and position of scapulae [19]. Higher errors have been found in patients with more severe scoliosis and this could be potentially avoided by using a larger dataset and having more information of related surfaces. In addition, maintaining the same pose during X-ray acquisition and 3D scans would decrease the error related to mismatching (rigid fusion) of positions between the two scanning procedures. This could be also reduced by placing radiopaque markers on the skin at the key anatomical landmarks. These markers would be visible on both modalities and thus indicate visually if there is a mismatch between images.

V. Conclusion

The results presented in this paper show development of prediction model to generate internal spinal alignment from 3D back surface and evaluated errors for both frontal and sagittal plane. In most cases the predicted curves approximate the real shape of the ground-truth spinal curve with a reasonable error, comparable to previous studies. Anyhow, the model could be significantly improved by increasing the number of samples, that would also allow to implement and train machine learning algorithms to correlate internal and external curves especially in more severe AIS cases. Moreover, better matching between 3D surface scans and X-ray radiographic images may increase the accuracy of regression and prediction. Additional information about the shape and position of the bones below the skin (e.g., shoulders, scapulae, rib cage) could lead to the solution to predict another important internal parameters related to scoliosis, such as CAs, vertebra rotations, pelvis tilt, etc. Future direction in data collection will also include higher number of moderate to severe AIS cases.

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