Human Spinal Column Diagnostic Parameter Identification Using Geometrical Model of the Vertebral Body ⋆

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Abstract:
A geometric model and related methods to easily define patient specific vertebral body models have been introduced in our previous studies. This paper proposes an angle measurement method that can be fully automated after the definition of the patient specific vertebral body model. A Principal Component Analysis based algorithm allowing the quick identification of the symmetry plane of the human spline is also developed and described. The clinical dataset used to analyse and validate the models and methods introduced consists of 39 patients' lumbar section of the spinal column with 195 vertebrae.
In terms of angle measurement the proposed geometric model and the measurement method is proven to be accurate enough for clinical diagnostics, the average mean value of the measurement error 0.15° and 0.75° comparing the measurements to the two reference datasets. The average standard deviation of the error was around 2.50° that is almost the same as the average standard deviation of the two reference datasets (2.34°).

Keywords: Geometric modelling, symmetry plane definition of human spinal column, principal component analysis, vertebral body model, automated angle measurement

1. INTRODUCTION

Multi-purpose reference databases of spinal column anatomy consisting of commonly used diagnostic parameters, e.g. specific angel between anatomical structures, bone volumes, etc. have several benefits in human research and clinical diagnostics (Zhou et al. (2000)). However, the creation of these databases is challenging due to the time consuming manual processing of the clinical data. In our recent study (Bazso (2020)) a geometric model and related methods to easily define patient specific vertebral body models have been introduced that can facilitate the creation of such diagnostic databases and effectively support the clinical diagnosis (Bazso et al. (2021)).

Supporting orthopaedic diagnostics by angle measurement automation on 2D and 3D medical images is an intensively researched area due to its benefits on medical care. The angle measurement on 2D radiographs (Tu et al. (2019)) is more common as recognizing 2D projections of the bones is more accessible than the segmentation and identification of the 3D bone structures (Tu et al. (2019)). Both traditional image processing methods (Safari et al. (2019)) and artificial intelligence methods (Horng et al. (2019) and Cho et al. (2020)) are applied in the automated angel measurement procedures. However, all the proposed methods require manual intervention (Safari et al. (2019) and Allen et al. (2008)). In the case of 3D image based measurement it is an additional challenge to identify the plane used for the measurements, which should be practically the symmetry plane of the spinal column in the non-pathological cases.

This paper proposes an angle measurement method that can be fully automated after the definition of our patient specific vertebral body model suggested in our previous articles (Bazso (2020) and Bazso et al. (2021)). The technique can be used to create clinical diagnostic parameters of the human spine automatically. The automation required identifying the symmetry plane of the human spine that will serve as a measurement plane. Thus, a Principal Component Analysis based algorithm allowing the quick identification of the human spline's symmetry plane is also proposed.

The paper presents the clinical dataset used to validate and analyse the proposed models and methods consists of 39 patients' lumbar section of the spinal column with 195 vertebrae. The reference data base included 15 different bone surface angle measurements for each patient

⋆ The research was supported by the Hungarian National Scientific Research Foundation, Grant No. K116574, by the NRDI Fund (TKP2020 IES,Grant No. BME-IE-BIO) and by H2020 MSCA-RISE DCPM (#872488) grant.

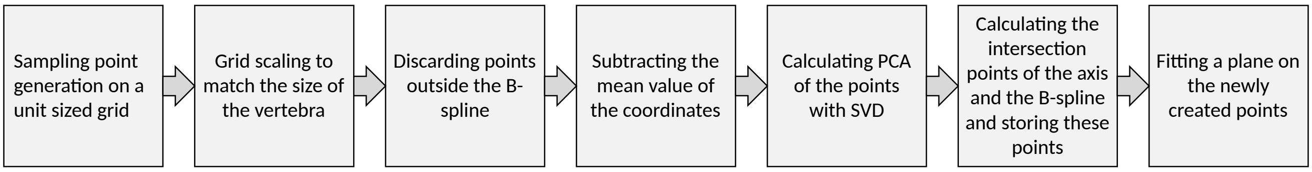

Fig. 1. Flowchart of sampling point generation

measured by two clinicians. The symmetry plane identification algorithm is validated using five randomly selected patients.

The subsequent section will introduce the symmetry plane identification algorithm and its parameter optimization, the details of the clinical dataset, and the validation methods applied. The measurement results and the comparison of the results with the reference dataset is presented in Section 3. It is followed by the discussion of the results in Section 4. The results are summarized in the last section.

2. METHODS AND DATA

2.1 Geometric model and modelling framework

The geometrical modelling of the vertebral body was done using the model introduced in our recent studies (Bazso (2020) and Bazso et al. (2021)). The model is defined by geometrical curves, more precisely with B-splines and quadratic functions. The benefit of the mathematically defined curves over a triangular mesh is the ability to evaluate the curve at any point without loss of precision. The model is defined by marking key anatomical points in three parallel planes. The outline of the vertebral body's base plates are marked to correctly represent the shape and height of the anatomical structure. In order to model the dent of the vertebral body's side a third plane is necessary in between them. In the next step a B-spline is fitted on the markers in each plane thus creating the two base plate's model. The best fitting curve is selected by minimising the distance of the curve from the markers. The side of the vertebral body is modelled by connecting these B-splines with a curve defined by a quadratic function.

The framework used for the modelling was an environment originally built for aortic valve modelling and simulation (Umenhoffer et al. (2018)). Although the task is different from medical perspective, there are lot of similarities in the engineering requirements. Both of them are a modelling task, where a model has to be co-registered with the medical image.

2.2 Angle measurement automation

In medical practice the angles of the vertebral column are measured in the central sagittal plane, that goes through the symmetry axis of the vertebral bodies (Kehr (2015)). Usually the frameworks used in clinical practice enable the medical expert to rotate the image in order to properly align it. This process requires some practice and manually measuring all the angles could be time consuming.

In the first step of the automatic angle measurement process the symmetry plane of the spinal column has to be determined. The shape of the vertebral body's base plate can be approximated with an ellipse. Therefore, by fitting an ellipse on the points of the base plate the symmetry axis can be determined.

The angles are measured in the sagittal plane by calculating the plane and the B-spline's intersection points. These points designate the line that lays on the sagittal plane and the vertebral body's base plane. In the final step the angles of these lines are calculated thereby measuring the angle of the different base plates of the vertebral bodies.

2.3 Symmetry plane definition method

The steps of the symmetry axis fitting algorithm is shown in Fig. 1. In the initial step points are generated in a square shape on a grid. Then the grid is scaled to match in size with the B-spline of the base plate and the points outside the curve are discarded. The ellipse fitting is done with PCA (principal component analysis) using these points.

PCA is usually used for dimension reduction to change the basis of the coordinate system and use only the most significant dimensions of the converted coordinate system. The first basis given by the PCA will be the vector defining the line that fits best to the given points, i.e. minimises the average square distance of the points from the line. All other bases will be orthonormal with the previously defined ones. They are created on the same way as the first one. The first two bases could be used to define the best fitting ellipse for the given points in the plane defined by the first two dimensions. Since our points always sit on a plane PCA could be used for the ellipse definition in our case.

There are several ways to calculate the PCA with given points, in our implementation we used SVD (Singular Value Decomposition). SVD is used for matrix factorization in linear algebra. To calculate the PCA with SVD the data has to be centred. This is achieved by calculating the mean value of the point's coordinate and then subtracting the result from each point's coordinate. The first principal component gives the symmetry axis's normal of the vertebral body's base plate. In the next step the intersection point of the symmetry axis and the B-splines are calculated. With each vertebra this process yields 4 points on the symmetry plane of the vertebra. To position the sagittal plane a plane fitting algorithm was implemented. This process takes the aforementioned 4 points of each vertebra and fits a plane using the above introduced PCA. The third component will represent the direction that is perpendicular to the plane meaning it is an optimal candidate for being a normal vector of the sagittal plane.

2.4 Validation and parameter optimisation of symmetry plane definition

Without reference data that could be used as ground truth in the validation of the symmetry plane method we developed a process to get quantitative result. To measure the achieved result we exported the model and its mirrored version on the symmetry axis as a voxel array. Then compared the two binary voxel array by evaluating a dice coefficient. Higher value means a better fit on the symmetry axis. This value is below 100%, because 100% is only achievable if the vertebrae are perfectly symmetrical.

It is important to find the ideal number of points for this algorithm. By selecting too few points the plane at the end will represent poorly the vertebral bodies symmetry axis. In contrast selecting too many points will not increase the precision, but will slow down the process due to the computation intensive algorithm. We were looking for the point where the diminishing return made unnecessary to increase the point count. For the quantitative comparison of the volumes we applied the commonly used Dice coefficient.

2.5 Dataset

CT images for this study were selected from patients' record who were subject to a full body CT scan. They were examined in an 8 year period between 2012-2020 in the National Trauma Center. The patient were selected from three different age groups (20-31, 31-40 and 40-51 year-old), in each group there were 7 male and 6 female subjects. The selection process had two criteria. First all patients in this study were scanned in supine position, second any patient with spinal column injury or other degenerative changes on the vertebral column were excluded. The anonymisation of the CT scans were performed according to GDPR.

The reference dataset were created by measuring the selected angles manually using the medical software in the hospital.

3. RESULTS

3.1 Optimal parameters and accuracy of the symmetry plane definition

The optimization steps are detailed in Section 2.4. Five patients were selected to define the optimal number of sampling points used for the PCA calculation in the symmetry axis fitting algorithm. We evaluated the Dice coefficient (as introduced in Section 2.4) with 3 different versions of the method. Fig. 2 shows the achieved results, 16 sampling points yielded poor results, while 144 had no practical benefit over the case with 64 sampling points, that were used later in the study.

The accuracy measurement process was detailed in Section 2.4. Table 1 shows the achieved Dice coefficients when 64 points were used. All of the measured values are over 88%, meaning the plane represents the symmetry plane with high degree of precision.

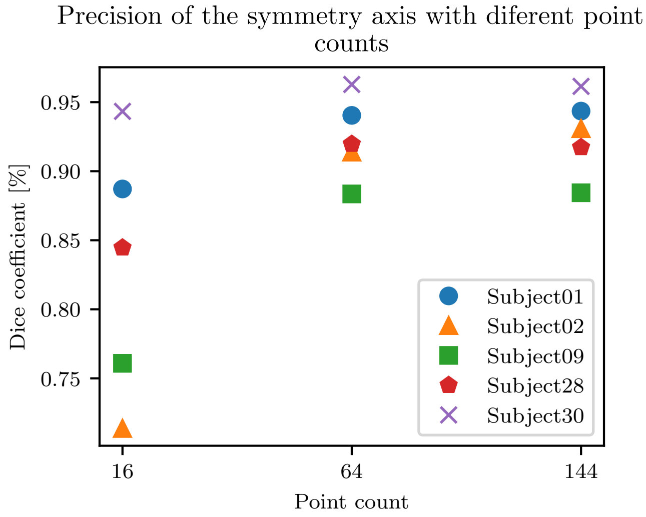

Fig. 2. Precision of the symmetry plane identification with different number of sampling points

Table 1. Dice coefficients with 64 points

Subject01	Subject02	Subject09	Subject28	Subject30
94.0%	91.4%	88.4%	92.0%	96.2%

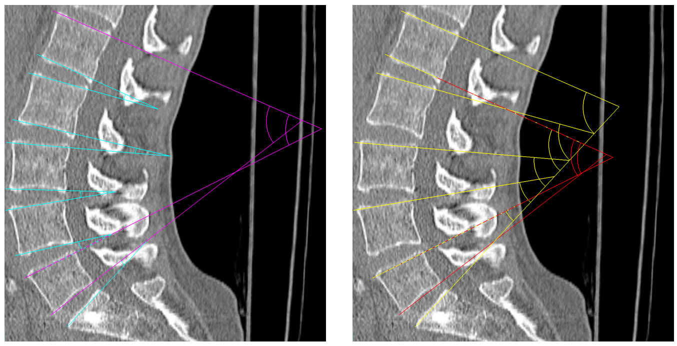

Fig. 3. Measured angles on the lumbar section of the spinal column

3.2 Measured diagnostic parameters

15 angles of the lumbar section of the vertebral column was selected for this analysis. These angles were chosen to contain at least one measurement for both base plates of each vertebrae. Fig. 3 shows in a sagittal plane the 15 angles, while Table 2 lists all 15 angles along with the minimum and maximum measured value in the dataset.

Fig. 4 shows the measured angles separately for male and female subjects organized in age groups. Although one specific angle shows great variation even in the same gender and age group they follow the same trend, due to the curvature of the lumbar lordosis.

3.3 Results of the automated measurements

The angle measurement were validated by comparing the model's result with the manually measured angles. The medical tool used for the measurement had 1.0° precision. This means the best achievable angle difference between the angle calculated from the model and the reference is 0.5°.

Table 2. Measured angles on the lumbar section of the spinal column

Angle			Min [°]	Max [°]
Sacrum	-	L05 TOP	16.0	34.9
Sacrum	-	L04 TOP	26.7	52.6
Sacrum	-	L03 TOP	34.7	65.4
Sacrum	-	L02 TOP	36.6	73.8
Sacrum	-	L01 TOP	32.5	76.0
Sacrum	-	L01 BOT*	38.1	87.4
L01 TOP	-	L05 BOT**	14.4	63.4
L01 TOP	-	L05 TOP	5.6	50.2
L01 BOT	-	L05 TOP	11.2	54.9
L01 BOT	-	L05 BOT	18.5	74.9
L01 BOT	-	L02 TOP***	-2.2	16.8
L02 BOT	-	L03 TOP***	-2.8	12.1
L03 BOT	-	L04 TOP***	-1.4	12.7
L04 BOT	-	L05 TOP***	5.2	19.0
L05 BOT	-	Sacrum***	6.0	24.1

*Lumbar lordosis angle
**Lumbar lordotic angle
***Wedge angles
Positive value represents posterior direction
while negative value corresponds to anterior direction.

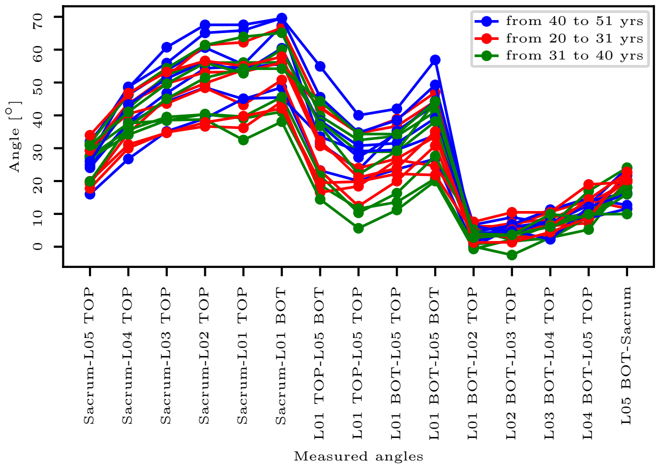

Fig. 4. Measured angles for 21 spinal columns

Using the mean value and the standard deviation a normal distribution is fitted to the data, in Fig. 5 and 6 the CDF (Cumulative Distribution Function) of each measured angles is shown.

Table 3 shows the mean and the standard deviation each of the fitted normal distributions and also the average of those two statistical parameters. Since we had two reference measurements the measurement error is shown for both of the references (reference#1, reference#2) and the statistical parameters of the difference between the two references are also presented. As it can be clearly seen based on the statistics the measurement error is in the same value range than the uncertainty of the reference data. The measurement angles are definitely in the physiological range reported in other studies (van der Houwen et al. (2010)). The measurement error is in the same range or lower than reported measurement error in similar studies (Langensiepen et al. (2013)).

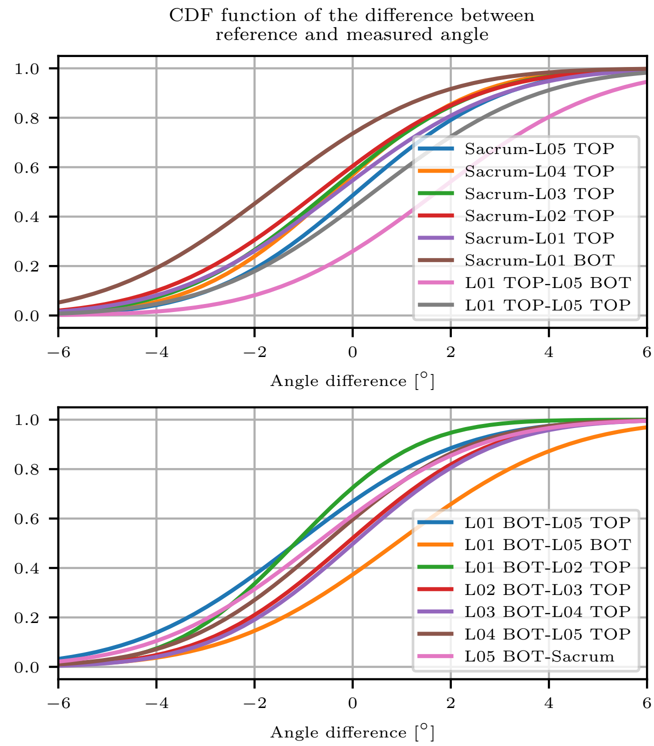

Fig. 5. CDF function of the difference between measured and reference#1 angle

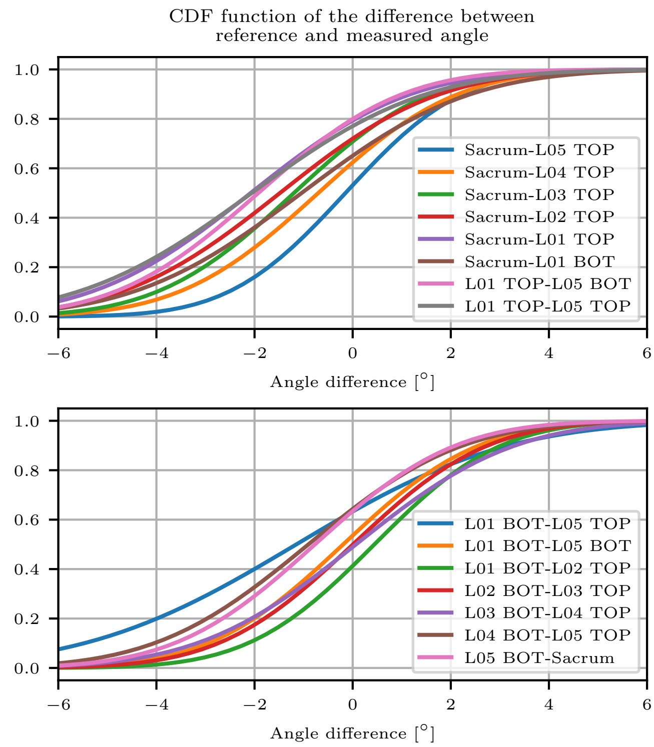

Fig. 6. CDF function of the difference between measured and reference#2 angle

4. DISCUSSION

By analysing the measured angles (Fig. 4) a trend can be seen where the angle between the Sacrum and the different

Table 3. Difference between measured and reference angles

Angle	Ref1-Meas Mean	Ref1-Meas Std	Ref2-Meas Mean	Ref2-Meas Std	Ref2-Ref1 Mean	Ref2-Ref1 Std
Sacrum-L05 TOP	0.21	2.37	-0.02	1.86	-0.23	2.02
Sacrum-L04 TOP	-0.27	2.27	-0.58	2.22	-0.31	2.36
Sacrum-L03 TOP	-0.35	2.43	-1.07	2.19	-0.72	2.09
Sacrum-L02 TOP	-0.56	2.58	-1.36	2.54	-0.79	1.96
Sacrum-L01 TOP	-0.18	2.65	-1.95	2.54	-1.77	1.91
Sacrum-L01 BOT	-1.56	2.66	-0.92	2.69	0.64	2.31
L01 TOP-L05 BOT	1.84	2.67	-1.80	2.29	-3.64	2.95
L01 TOP-L05 TOP	0.56	2.64	-1.93	2.78	-2.49	2.60
L01 BOT-L05 TOP	-1.02	2.62	-1.02	3.38	0.00	3.47
L01 BOT-L05 BOT	1.01	2.74	-0.07	2.16	-1.08	2.31
L01 BOT-L02 TOP	-1.05	1.96	0.57	2.01	1.62	2.55
L02 BOT-L03 TOP	0.00	2.33	0.13	2.14	0.13	2.27
L03 BOT-L04 TOP	0.14	2.31	0.19	2.53	0.05	1.93
L04 BOT-L05 TOP	-0.44	2.34	-0.78	2.45	-0.33	1.97
L05 BOT-Sacrum	-0.62	2.60	-0.64	2.24	-0.03	2.39
Means:	-0.15	2.48	-0.75	2.40	-0.60	2.34

vertebrae of the spinal column increases from the bottom base plate of the L05 to the top one on L01. This correlates with the physiological curve of the lumbar section of the vertebral column, where the lumbar lordosis dominates.

Fig. 5 and 6 describes the absolute angle difference between the reference dataset and the calculated angle from the model. Majority of these curves has a mean value between minus one and one, where zero would be the ideal value. However, there are some curves that lies outside this range. It is worth to mention that the angles studied in this paper are not independent from each other. The reason is that some angles share a common arm when the same vertebra being used in multiple angle measurements. This is most notable with *Sacrum - L01 Bottom* and *L01 Bottom - L02 Top* angles, because both show extreme deviation from the ideal curve.

Table 1 summarises the precision of the automatic symmetry plane fitting algorithm. With average score of 92.4% it is considered exceptional taking into account the fact that the vertebrae are not perfectly symmetrical. Fig. 2 showed us that the optimal number of points are near 64, from there increasing the point count does not provide any practical benefit. One of the key factors in the effectiveness of this algorithm is the usage of multiple vertebrae in the fitting process thereby reducing the effect caused by the low precision in the process of finding the symmetry plane of a single vertebra.

The angle calculation process only takes a few seconds, but it requires a geometrical model. The definition of this model takes considerable amount of time, but it can be used for other purposes than angle measurement, as well. One of the key benefit of performing the angle measurement based on the model is the reproducibility. Other advantage over the traditional angle measurement process is that it preserves addition. This means by adding angle *L01 Top - L02 Top* and *L02 Top - L03 Top* the result will be the angle of *L01 Top - 03 Top*. This assumption will not be fulfilled with traditional angle measurement process because it is possible that the medical professional marks the *L02 Top* slightly differently when measuring the two angles.

Fig. 7. Uneven surface of the vertebral body's base plate cause difficulty with both modelling and manual angle measurement

Currently the modelling process is time-consuming which makes its application impractical when the only goal is to determinate the angles. The modelling of the lumbar section of the spinal column requires on average one hour (12 minutes / vertebra), while measuring these angles with a clinical framework takes 15-20 minutes. In the future our goal is to improve the model definition process to decrease the time required for it.

The greatest difficulty in modelling and manual angle measurement is caused by the uneven vertebral body base plate surface, because the modelling process fits a plane, while the angle measurement fits a line on the vertebra. One example for this is shown in Fig. 7.

In our study we analysed 39 peoples CT image. The examination of the patients were done in the same hospital. Previously in a smaller study (Bazso et al. (2021)) we validated the model on a different database. The modelling in the current study was performed by 3 people. In the future to present the robustness of the model we would like to validate our model on images from different sources and model the same spine by multiple experts to determinate the reproducibility of the process.

5. CONCLUSION

In this study the geometric model and diagnostic parameter measurement methods have been validated using clinical dataset consisting 21 male and 18 female patients and total of 195 vertebrae. For the automatic measurement of the commonly used diagnostic angles of the lumbar spine principal component analysis based symmetry plane definition method of the spinal column is defined and also validated using the clinical data.

In terms of angle measurement the proposed geometric model and the measurement method is proven to be accurate enough for clinical diagnostics, the average mean value of the measurement error 0.15° and 0.75° comparing the measurements to the two reference datasets (Table 3). The average standard deviation of the error was around 2.50° that is almost the same as the average standard deviation of the two reference datasets (2.34°).

Based on the results presented the proposed geometrical model and the related geometrical model is found to be appropriate for semi automated processing of human CT scans of the spinal column. The model based volume measurement method has been validated in a previous study(Bazso et al. (2021)), the angle measurement in this current study. Based on these results it is possible to initiate the development of a larger scale multi purpose reference database of the spinal column anatomy. Validation on a larger scale database would be beneficial and necessary before direct application of the methods in the clinical practice. However, based on the results presented the proposed methods could be directly applied in clinical diagnostics and research.

6. ACKNOWLEDGEMENT

The authors would like to express their gratitude to Dr. Tamás Umenhoffer for helping them to setup the modelling framework, assisting and giving advices for it's usage. We are grateful for Prof. Tamás László Várady and Dr. Péter Salvi for their help in the design of the model and for so kindly supporting us in the creation of the model. We would like to express our gratitude to László Szilágyi for his help in the development of the symmetry plane fitting algorithm. We would like to thank Diána Kőrösi and Dóra Kapui for their help in the modelling.

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