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An Efficient Superimposition Method for Surgical Planning Assessment

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Introduction

Based on well development of computer technology and computer graphics, computer-aided surgical planning has been widely used to enhance predictability and safety of surgery, looking forward to reducing the operation time [1]. To validate the plan with surgical outcomes accurately is an important issue to improve the use of guiding tools for minimizing the difference. To access the differences between surgical planning and post-surgical outcomes, superimposing models or image of affected site of these two stages is necessary [2]. Iterative closest point (ICP) algorithm is the most popular approach to achieve the best match between two objects [3]. The ICP methods achieve perfect matching of two point clouds with almost the same shape. However, for some deformed bones after surgery, the outcomes of kernel body superposition were yet to be optimized, hence, manual adjustment was conducted subsequently. The authors found that even if the affected vertebra contained partially embedded metal implants after spinal surgery, its shape still remained symmetric.

The aim of this research was to develop a robust superposition method for surgical planning and outcome evaluation using the symmetrical characteristic of the affected site. The method is applicable to any type of more or less symmetrical organ, especially the vertebrate bones. Artificial vertebrae models were used to simulate the local deformation caused by spinal surgery to verify the deviation of the proposed algorithm.

[1] Wu, H. H., Su, I. C., Hsieh, C. T., Fang, J. J., and Chang, C. J., "Accuracy and safety of using customized guiding templates for cervical pedicle screw insertion in severe cervical deformity, fracture, and subluxation: a retrospective study of 9 cases," World neurosurgery 116, e1144-e1152 (2018).
[2] Sipari, S., Iso-Mustajarvi, M., Lopponen, H., and Dietz, A., "The insertion results of a mid-scala electrode assessed by MRI and CBCT image fusion," Otology & Neurotology 39(10), e1019-e102 (2018).
[3] Besl, P. J. and Mckay, N. D., "A method for registration of 3-D shapes," Ieee Transactions on Pattern Analysis and Machine Intelligence 14(2), 239-256 (1992).

Materials and Methods

Optimal symmetry plane

Based on computer tomography (CT), a voxel-based method was used in this study to find the OSP of bony tissues in vertebrae. The Optimal symmetry plane (OSP) was computed using an optimized algorithm to find the plane that had the maximum number of voxel pairs of bilateral parts. Based on this unique OSP, the degree of asymmetry can be quantified [4].

$$\max_{\varphi,\theta,d} f = \frac{\iiint [v(x,y,z) \times \bar{v}(x,y,z)]dxdydz}{\iiint dxdydz},$$

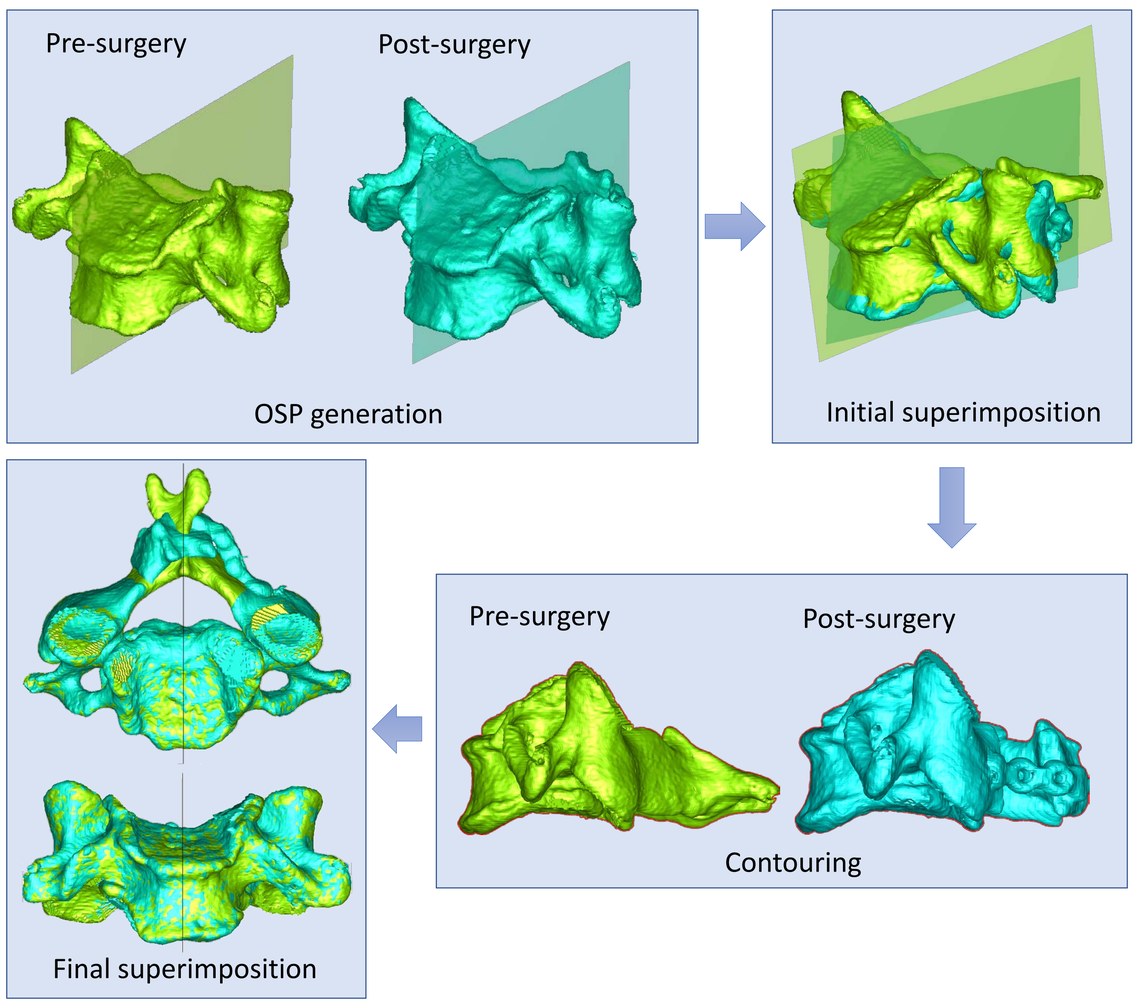
$$v(x,y,z) \times \bar{v}(x,y,z) = \begin{cases} 1, v(x,y,z) = \bar{v}(x,y,z) \\ 0, v(x,y,z) \neq \bar{v}(x,y,z) \end{cases}$$

where v(x, y, z) is the original voxel function, and $\bar{v}(x,y,z)$ is the bilateral voxel function corresponding to a given plane.

[4] Hsiao, Y. C., Chang, C. J., and Fang, J. J., "Quantitative asymmetry assessment between virtual and mixed reality planning for orthognathic surgery-a retrospective study," Symmetry-Basel 13(9), 1614 (2021).

OSP-based superposition method

An efficient and stable strategy is proposed to prevent such situations by using the characteristic of symmetry. The OSP of pre and post-surgical of affected site was generated, respectively. The complex iterative processes of the ICP algorithm were reduced from 3-D geometries to 2-D contours in which the object vertices were projected onto their OSP. Efficiency advantages ensued due to the decreased number of point matching computations.

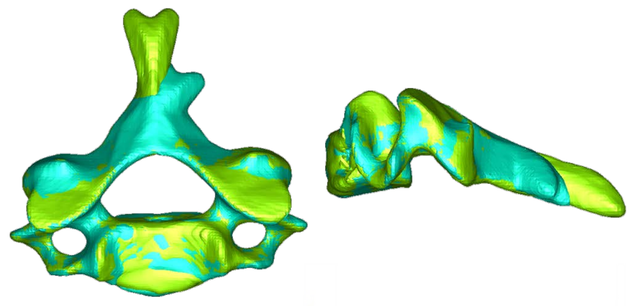


The singular value decomposition is applied to calculate the rotation matrix which minimizes the deviation between two 2-D point clouds for superimposing them. If the difference between the last two iterations is less than the threshold, the algorithm has converged. The condition of convergence is defined as the difference between the overlapped areas of the two contours between two iterations less than 0.001 mm^2

Verification

Digital models of two groups of ten vertebrae each were used in this experiment, including cervical (C3–C7) and thoracic (T4-T8) vertebrae. There was no deformation in the pre-surgical group, but each vertebra in the post-surgical group had one deformation each at the +y side to simulate surgical destruction. To quantify the deviation between the superimposed pre- and postsurgical vertebrae, three holes were designed to embed aluminum beads as markers in the same position on each vertebra in the two groups. The two groups were scanned by CT and reconstructed with a 1-mm slice. All the beads were reconstructed with the same imaging threshold. The center of each bead was calculated by spherical fitting with a radius deviation of less than 0.02 mm.

Artificial vertebrae



Superposition result of artificial C5 vertebrae

The superposition deviation of the whole vertebra, the vertebral body on average of each vertebra, and the average deviation of the three beads on each vertebra are listed. All vertebrae were superimposed successfully in the experiment. The maximum and minimum deviations of a single bead were 0.66 mm and 0.06 mm respectively.

Vertebrae level	Vertebral body superposition deviation	Beads deviation on average
C3	0.26±0.35	0.43
C4	0.28±0.17	0.20
C5	0.15±0.25	0.27
C6	0.28±0.13	0.27
C7	0.26±0.27	0.21
T4	0.33±0.24	0.37
T5	0.27±0.33	0.17
T6	0.34±0.26	0.30
T7	0.31±0.24	0.44
T8	0.27±0.15	0.13
Average	**0.28±0.25 mm**	**0.28±0.15 mm**

Discussion and Conclusions

The maximum superposition deviation of the vertebral body was 0.34 mm. The result indicated that even after the same vertebral body has undergone manufacturing (deviation of 0.01 mm), scanning, and reconstruction processes (deviation of 0.34 mm), some difference exists. Therefore, in this study, the OSP was used as a robust standard to find the contours of two objects for superposition, to avoid the effect of other factors on the superposition results.

In this research, the optimal-symmetry-plane based iterative closest point algorithm was developed to superimpose the same object from different sources or two objects with slight deformations. This technique can be applied for post-operative analysis, such as quantifying the deviation between surgical outcomes and targets, or be used as a measurement for long-term medical follow-up.