A novel method for 3D face symmetry reference plane based on weighted Procrustes analysis algorithm

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Research article

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Abstract

Background: We aimed to establish a novel method, using the weighted Procrustes analysis (WPA) algorithm, which assigns weight to facial anatomical landmarks, to construct a three-dimensional facial symmetry reference plane (SRP) for mandibular deviation patients.

Methods: Three-dimensional facial SRPs were independently extracted from 15 mandibular deviation patients using both our WPA algorithm and the standard PA algorithm. A reference plane was defined to serve as the ground truth. To determine whether the WPA SRP or the PA SRP was closer to the ground truth, we measured the position error of mirrored landmarks, the facial asymmetry index (FAI) error, and the angle error for the global face and each facial third partition.

Results: The average angle error between the WPA SRP and the ground truth was 1.66 ± 0.81°, which was smaller than that between the PA SRP and the ground truth. The position error of the mirrored landmarks constructed using the WPA algorithm in the global face (3.64 ± 1.53 mm) and each facial partition was lower than that constructed using the PA algorithm. The average FAI error of the WPA SRP was -7.77 ± 17.02 mm, which was smaller than that of the PA SRP.

Conclusions: This novel automatic algorithm, based on weighted anatomic landmarks, can provide a more adaptable SRP than the standard PA algorithm when applied to severe mandibular deviation patients and can better simulate the diagnosis strategies of clinical experts.

Background

Mandibular deviation is one of the more common manifestations of facial asymmetry, accounting for 70 % – 80 % of all cases[1-3]. The restoration of symmetrical, coordinated, and aesthetic facial shapes is a central focus of oral and maxillofacial surgery, orthodontics and prosthodontics[4-6]. Using three-dimensional digital technology, the extraction of the symmetry reference plane (SRP) is the primary step during symmetry analysis of three-dimensional facial data[7]. SRP accuracy directly affects the symmetry index and is critical for developing treatment strategies and evaluating treatment progress.

The traditional methods for extracting an SRP are often based on medical and bilateral anatomical landmarks measured either using a digital three-dimensional facial model or having the head in a natural position[8-11]. These methods are widely used, but since landmarks definition varies, establishing common methods suitable for different types of facial asymmetry remains challenging [12, 13]. In recent years, an SRP extraction method, referred to as the original-mirror alignment method, based on superimposed three-dimensional original and mirror facial data has received an increasing attention.

This method involves superimposing a three-dimensional geometric shape of a facial model (the original model) onto its mirror model[14]. The SRP of the original model is determined by analysing the superimposed model's symmetry plane, which are geometrically symmetrical. The most critical step of this method is the three-dimensional superimposition, which primarily involves the iterative closest point
(ICP) and Procrustes analysis (PA) algorithms[15, 16]. The ICP algorithm seeks optimal superimposed position of the three-dimensional original and mirror models composed of tens of thousands of point clouds determined by an iterative solution[17]. Based on 1:1 ratio between the original and mirror landmarks (anatomical landmarks or mathematical facial mask), the PA algorithm obtains the superimposed position with minimum average distance between the two sets of landmarks through a matrix operation (translation, rotation, and scale) [18-21]. SRP extraction, using PA algorithm, relies more on facial landmarks than it does when using ICP algorithm. Furthermore, the PA algorithm is more aligned with stomatological clinical diagnosis and treatment and has thus received significant attention in recent years.

Xiong et al. reported that PA algorithm can be used to extract facial SRP using 21 important anatomical landmarks. While this algorithm is suitable for normal facial data, it is not ideal for facial asymmetry data (particularly data from patients with complex facial deformities) since it does not assign weights to individualised facial features (different degrees of asymmetry). There remains a discrepancy between the algorithm results and the logical basis of oral clinical diagnosis[22].

Based on standard PA algorithm studies, this study aims to establish a weighted Procrustes analysis (WPA) algorithm for extracting a three-dimensional facial SRP that can automatically recognise weight assignment of facial landmarks. Our study analysed and evaluated the WPA algorithm suitability for commonly observed clinical cases of mandibular deviation.

**Methods**

Due to technical limitations, the methods section is only available as a download in the supplementary files section.

**Results**

3.1 Analysis of angle error

The K-S normality test for angle error (of two groups of 15 values each) showed that both groups conformed to the normal distribution. Data analysis yielded no significant differences (P > 0.05) between the PA and WPA algorithm groups. Measurement analysis showed that the mean and standard deviation of the angle error in the PA and WPA groups were 2.16 ± 1.08° and 1.66 ± 0.81°, respectively. Since the mean and standard deviation of the angle error of the WPA algorithm group were smaller, this indicates that the SRP constructed using the WPA algorithm for the 15 data points was closer to the ground truth plane.

3.2 Analysis of position error

Table 1 shows the measurement values for the position error between the test groups for global landmarks (two groups of 15 values each) and regional landmarks (six groups of 15 values each). The K-
S normality test for position error revealed that all groups conformed to the normal distribution. There were significant differences in the position errors among the groups (P < 0.05).

Tukey's honesty significance test revealed significant differences (P < 0.05) between the lower and upper facial partitions in the WPA group, between the lower and upper partitions in the PA group, and between the lower and middle partitions in the PA group. Related sample data distribution and statistical analysis results are shown in Fig. 4.

The mean and standard deviation of the global position error of the WPA and PA groups were 3.64 ± 1.53 mm and 4.54 ± 1.92 mm, respectively; the mean and standard deviation of the position error of the WPA algorithm group were smaller than those of the PA group. Among the six groups of regional facial data, the position errors of the upper, middle, and lower partitions in the WPA group were 2.38 ± 1.15 mm, 3.27 mm ± 1.29 mm, and 4.63 ± 2.28 mm, respectively; the position error was lowest in the upper partition. The difference between the lower partition error and the global mean position error was 0.99 mm.

In the PA group, the position errors of the upper, middle, and lower partitions were 3.67 ± 1.84 mm, 3.77 ± 1.51 mm, and 6.35 ± 3.23 mm, respectively; the position error was highest in the lower partition. The difference between the lower partition error and the global mean position error was 1.81 mm. These results showed that the global and regional errors of the WPA group were smaller than those of the PA group. Additionally, the lower partitions weighted overlap result of the WPA group was closer than that of the PA group to the weighted overlap result of the reference group, demonstrating a significant improvement in the WPA group compared with the PA group.

### 3.3 Analysis of FAI error

The K-S normality test for FAI error (in two groups of 15 values each) showed that both groups conformed to the normal distribution. Data analysis yielded no significant differences (P > 0.05) between the PA and WPA groups. There were no significant differences between the FAI errors of both groups (P > 0.05). Measurement analysis showed that the average FAI errors calculated with the WPA and PA algorithms were 13.65 ± 12.45 mm and 15.77 ± 14.32 mm, respectively. The result of the WPA-calculated SRP was closer to the SRP of the ground truth plane than the PA-calculated SRP.

### Discussion

#### 4.1 The WPA SRP was more closely aligned with the ground truth plane than the standard PA SRP

The weighted algorithm is an important innovation of this study. The degree of the landmarks symmetry could be evaluated quantitatively and used as landmark weight factors to construct an SRP. Our WPA algorithm is designed to assign a small weight for landmarks with poor symmetry, post initial global ICP superimposition of the original and mirror models, and a large weight for landmarks with good symmetry. The weight calculation method was based on the reciprocal of the distance between the paired landmarks, which represents an inverse relationship between the distance and the corresponding
assigned weight. Based on superimposition using least-weighted squares, all original and mirror PA landmarks were assigned different weights. The solution to the PA landmark set system (the WPA objective function) was minimised, thus achieving an optimal overlap result of the original and mirror landmarks.

The results indicated that the average angle error of WPA group for all enrolled patients with mandibular deviation was < 2°, although there was no significant result when compared with the average angle error of the standard unweighted PA algorithm (of which the error was > 2°), the result of the WPA SRP was closer to the ground truth (Fig. 2), and the angle error displayed a downward trend.

Wu et al. showed that the angle difference between the two planes is easily perceived when it is > 6° [23]. The angle error between the WPA SRP and the reference plane was < 2°, which indicates that the accuracy of the WPA SRP was almost equal to that of the reference plane and therefore had a better clinical suitability than the PA SRP. Furthermore, the stability level of the WPA algorithm, with a standard deviation of 0.81°, was significantly higher than that of the PA algorithm, which had a standard deviation of 1.08°.

Additionally, the FAI value calculated for the WPA algorithm was closer to the professional result than was the FAI value calculated for the PA algorithm. Furthermore, the WPA FAI for patients with mandibular deviation was closer to the ground truth plane than the PA FAI. These results confirmed that the WPA algorithm performed better than the PA algorithm in constructing facial SRPs for facial asymmetry (mandibular deviation).

4.2 A new SRP evaluation indicator: the position error of mirror landmarks

In previous SRPs studies of the face and skull, SRP evaluation indicators have primarily included the angle and FAI errors [24, 25]. These two indicators can assess the global proximity of SRP, but neither can quantitatively analyse facial landmark asymmetry. In this study, we proposed to use the position error indicator as a novel SRP evaluation tool.

The mirror landmarks differed between the test and reference SRPs for mirroring the original facial model, while the original model was the same between the test and reference groups. Table 1 indicates that the mean values of the global position errors of the WPA and PA algorithms were 3.64 mm and 4.54 mm, respectively, and that the difference between them was statistically significant. This indicates that the global overlapping degree of the WPA algorithm mirrored features and reference mirrored features was more accurate than that of the PA algorithm. The weight distribution of the WPA algorithm was also significantly more accurate than that of the PA algorithm; the weight factor of the WPA algorithm had a significant effect.

The mean value of the regional position error for the upper, middle, and lower partitions also reflected the degree of consistency between the weight distribution of the WPA SRP and the reference SRP for each facial partition. The mean position error of the WPA algorithm was smaller than that of the PA algorithm.
for all three facial partitions. This difference was significant, indicating that the WPA algorithm for each facial partition was close to the professional algorithm.

Additionally, the position error of the WPA algorithm for the upper and lower parts of the face was considerably smaller than that of the PA algorithm, while that for the middle part was close to that of the PA algorithm. This is because the WPA algorithm allocated a lower weight for lower facial landmarks to reduce their influence on the global overlapping degree, while the upper landmarks were assigned higher weights to increase the overlapping degree, thus accounting for professional experience in the weight distribution of the landmarks. Compared with the PA algorithm without weight distribution, the position error of the WPA in each region was optimised, and an ideal SRP construction result was obtained.

4.3 Limitations and further research to improve the three-dimensional facial SRP

Previous studies on the original-mirror alignment method are divided with regards to using the ICP and PA algorithms. Among them, ICP is an algorithm that does not refer to anatomical landmarks. Although the reliability and repeatability of the ICP algorithm have verified when used for constructing SRPs with data from patients with normal facial symmetry, facial asymmetry data affects algorithm's performance making SRPs construction unfeasible for patients with severe asymmetry. Scholars have since improved the global ICP algorithm by manually selecting facial regions with good symmetry for original and mirror models; the clinical suitability of this modified ICP algorithm has improved to some extent[26, 27]. This algorithm is referred to as the regional ICP algorithm, and although it reduces the degree of automation by introducing human interference, it remains suitable for use in oral clinics. Therefore, the regional ICP algorithm was used as the ground truth in this study to evaluate the accuracy of our proposed algorithm.

One of the differences between the PA and ICP algorithms is that SRP extraction using the PA algorithm relies more on anatomical facial landmarks, which is consistent with clinical diagnosis and treatment. PA algorithm is applicable for symmetry patients, but the asymmetric PA landmarks will have a Pinocchio effect on the PA algorithm[28].

One source of improvement is to filter PA landmarks. Landmarks have been sorted through the recursive PA algorithm, deleting the obvious asymmetric landmarks (outliers) and using the remaining for PA operation to avoid their interference [29]. However, for patients with complex facial deformities (in which most landmark symmetries are not ideal), this algorithm may eliminate too many landmarks and tends to be locally over-optimised.

Our study has proposed another way to improve the standard PA algorithm by adding a weighted system. We hypothesised that by analysing the distance between the corresponding original and mirror landmarks post initial alignment, the degree of symmetry could be evaluated quantitatively and used as landmark weight factors to construct an SRP with personalised feature weight assignments. Our WPA algorithm did not have a reduced degree of automation and could therefore simulate the expression of the reference value weight of anatomical landmarks assigned according to clinical experience. This is advantageous with regards to SRP construction. Our results also indicated that the WPA algorithm was
suitable for patients with complex mandibular deviation. However, the WPA algorithm tested in this study had some limitations.

First, the quantitative indicator of landmarks asymmetry (the reciprocal of the distance between paired landmarks) was indirectly obtained. To set the key parameters for the landmark weight factors, global ICP algorithm was used to initiate the registration of the original and mirror models. One-way to address this is to use an intelligent landmark weighting strategy based on direct morphological feature analysis, artificial intelligence, and deep learning technology, to improve the accuracy and rationality of landmark weight distribution leading to better SRP constructions that simulate expert clinical diagnosis.

Second, anatomical landmarks in this study need to be selected manually. We expect that our WPA algorithm will further combine mathematical facial mask, automatically extracting a general face mesh, thus improving its clinical suitability. Cases of mandibular deviation between 5 mm and 23 mm were quantitatively analysed in this study; although sample cases should be further expanded to evaluate our method’s suitability for different types and degrees of facial deformities to provide guideline for clinical application. Therefore, testing our method on samples representing a wider range of facial deformities is warranted.

**Conclusion**

The WPA SRP was more closely aligned than the standard PA SRP with the ground truth plane in terms of angle and FAI errors as well as global and regional position error, indicating that our novel method of assigning weights to facial landmarks had accurately constructed an SRP for patients with facial asymmetry. We also established the position error as an effective SRP analysis tool for facial asymmetry data. Our proposed method and findings can help stomatological clinical practices in both mandibular deviation diagnosis and treatment. In addition, this new method is not restricted to three-dimensional facial data and can be applied to skeletal models providing new solutions for dental clinical practise.

**Declarations**

**Ethics approval and consent to participate**

This study was approved by the Biomedical Ethics Committee of Peking University School and Hospital of Stomatology (No: PKUSSIRB-20163113). We declare that written informed consent was obtained from all participants included in the study.

**Consent for publication**

Written informed consent to publish individual person's images were obtained.

**Availability of data and materials**
The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

**Competing interests**

The authors declare that they have no competing interests.

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**Authors’ contributions**

YZhu performed data collection, statistical analysis and interpretation of results, drafted and revised the final manuscript. SZheng, GYang and XFu participated in study design and provided algorithm programming support. YZhao and YWang made substantial contributions to the conception and design of this study, and made a critical revision of the manuscript. All authors have reviewed and agreed to the submission of the final manuscript.

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Abbreviations

CCD Charge-coupled device
FAI Facial asymmetry index
FH Frankfort horizontal
ICP Iterative closest point
PA Procrustes Analysis
SRP Symmetry Reference Plane
WPA Weighted Procrustes Analysis

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Table

Due to technical limitations, Table 1 is only available as a download in the supplementary files section.

Figures
Figure 1

The 32 anatomic landmarks that are used in this study. (Upper facial third: trichion, glabella, superciliary ridge; Middle facial third: nasion, pronasale, subnasale, endocanthion, exocanthion, pupil, alare, subalare, zygion, tragion; Lower facial third: labiale superius, labiale inferius, sublabiale, pogonion, gnathion, cheilion, gonion, crista philtrre).

Figure 2

Determining the SRP based on WPA algorithm, PA algorithm and professional algorithm for one case. Red plane signifies SRP based on professional algorithm, green plane represents WPA algorithm, and yellow plane represents PA algorithm.
Figure 3

Position error of the mirrored landmarks. A, SRPs on original three-dimensional face, red colour plane signifies reference plane (SRP_Ref) and green colour represents WPA algorithm plane (SRP_WPA). B, Blue landmarks signify original landmarks. C, Reference mirror landmarks in red and WPA mirror landmarks in green, which were obtained from mirror original landmarks using SRP_Ref and SRP_WPA. D, Global position error was defined as the average distance of the 32 pairs of reference and WPA mirrored landmarks.

Figure 4

A diagram illustrating the process of calculating position errors using various algorithms and landmarks.
Workflow of the experimental procedures and evaluation methods. In the figure, WPA represents Weighted Procrustes analysis algorithm, PA represents Procrustes analysis algorithm. SRP_WPA, SRP_PA and SRP_Ref are symmetry reference planes constructed by WPA group, PA group and reference group respectively, LMK_WPA, LMK_PA and LMK_Ref are mirror landmarks constructed by WPA algorithm, PA algorithm and professional algorithm symmetry reference plane. FAI_WPA, FAI_PA and FAI_Ref are the facial asymmetry index (FAI) calculated by the SRP defined by WPA algorithm, PA algorithm and professional algorithm, Err_LMK_WPA and Err_LMK_PA are the global landmarks position errors of WPA and PA algorithms, under which Up, Mid and Low represent the position errors of different third parts. Err_Ang_WPA and Err_Ang_PA are the angle errors of WPA algorithm and PA algorithm. Err_FAI_WPA and Err_FAI_PA are facial asymmetry index (FAI) errors of WPA algorithm and PA algorithm.

Figure 5
Boxplot of position error for upper face, middle face, lower face group. The black asterisks signify $P < 0.05$ between WPA algorithm and PA algorithm group. The yellow and green asterisks indicate statistical significance for position error of different regional groups using a one-way ANOVA followed by Tukey’s multiple comparison test where $P < 0.05$, the circles within the boxplot represent outliers.

**Supplementary Files**

This is a list of supplementary files associated with this preprint. Click to download.

- Table1.docx
- Methods.docx