The Application and Accuracy of Feature Matching on Automated Cephalometric Superimposition

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Abstract

Background: The aim of this study was to establish a computer-aided automated method for cephalometric superimposition and evaluate the accuracy of this method based on free-hand tracing.

Methods: 28 pairs of pre-treatment (T1) and post-treatment (T2) cephalograms were selected. Structural superimpositions of the cranial base, maxilla and mandible were independently completed by three operators performing traditional hand tracing methods and by computerized automation using the feature matching method. To quantitatively evaluate the differences between the two methods, the manually superimposed patterns were digitized. In addition to registering automated and manual superimposition to digital T1 films, landmark distances between corresponding automated and manual T2 cephalometric landmarks were measured, and differences in manual superimposition among the operators were calculated.

Results: The T2 landmark differences in hand tracing between the operators ranged from 0.61 mm to 1.65 mm for the three types of superimposition. There were no significant differences in accuracy between manual and automated superimposition ($p > 0.05$).

Conclusions: Computer-aided cephalometric superimposition provides comparably accurate results to those of traditional hand tracing and will provide a powerful tool for academic research in the era of digital cephalograms and big data.

Trial registration: The clinical trial has been registered in April 1st 2016, the registration number is ChiCTR1800017694, URL is: http://www.chictr.org.cn/showproj.aspx?proj=29144

Background

Since the introduction of cephalometry in 1931 by Broadbent[1], it has become an important tool in clinical diagnosis, treatment planning, evaluation of treatment changes and growth study. Cephalometric analysis of linear and angular measurements between landmarks and superimposition analysis of series of cephalometric images are two main methods of cephalometry. The traditional method is hand tracing the craniofacial soft and hard anatomic structural contours on cephalograms on acetate paper. The process is subjective, and the accuracy varies with personal experience, knowledge, understanding and tracking preference[2–6]. Additionally, this process is time-consuming, and the accuracy is also inevitably influenced by the fatigue level of humans[7, 8]. In particular, for the purpose of research, a certain number of cephalograms need to be traced and measured within a certain time constraint, and the intra-/inter-reproducibility is impacted.

With the development of digital technology, traditional hand tracing cephalogram is being replaced by digital cephalometric analysis. In previous studies, the latter method using commercial software has been proven to be accurate, reliable and time saving[8–12]. However, the only exception is the structural superimposition for treatment evaluation and growth study, although much effort has been made in this field[3, 12–14]. The reason for this exception lies in the fact that landmark identification is essential for diagnosis purposes and is easy to fulfil using commercial software. In contrast, structural superimposition focuses on tracing of structural details, which is independent of landmarks, and is still not feasible using current commercial software.

Baumrind et al. claimed that magnification, tracing, landmark identification and measurements are major sources of error for cephalometric analysis [2, 15, 16] They believed that hand superimpositions on reference planes results in better quality than any computer-aided superimpositions because biological craniofacial growth is difficult to interpret by any mathematical equations[2]. However, due to its absolute consistency, fully automated cephalometric analysis has always been a popular challenge in computer science. One of these methods is the knowledge-based line extraction technique[17], which duplicates the strategy of orthodontists in which important anatomic edges are extracted and landmarks are located according to geometric definitions. However, the irregular details of bone, such as the inter-trabeculae, incisor nerve canal and inferior alveolar canal, make computer automated tracing difficult and questionable. Other studies have attempted to locate landmarks directly[18, 19], and the techniques have evolved from template matching [18] to, more recently, neural network models[19]. In terms of structural superimposition on stable regions instead of reference planes, which has been recognised as the most accurate method [20–24], why not use the same strategy? After all, the ultimate goal is to superimpose two cephalograms at two time points, and tracing the important structure is just simplification of a cephalogram, which facilitates the operation of orthodontists because complex overlapping craniofacial structures, especially bilateral ones, are difficult for human eyes to distinguish.

Recent studies [25, 26] have proposed improved computer algorithms for feature matching, whose mission is to detect and match keypoints of the same or similar regions in multiple images taken at different viewpoints, under different illuminations, or at different magnifications. In comparison with the traditional manual process of superimposing the structure on two cephalograms, the computer algorithm bears many similarities and could be applicable as an automated superimposition method. One of the algorithms, Oriented FAST and Rotated BRIEF(ORB)[25], was shown to be time saving for the matching process, rotational invariant and noise immune. However, two aspects of this method should be improved for it to be practical for clinical applications: (1) the area for detecting and matching keypoints should be limited in the stable regions on the cephalograms; (2) to achieve accurate matching results, the matches should be not only abundant but also of high quality.

Currently, there is no study that describes a method for automated cephalometric structural superimposition. Therefore, the present study aimed to (1) establish a computer-aided automated method of structural superimposition for the anterior cranial base, maxilla and mandible and (2) evaluate the accuracy of automated structural superimposition based on free-hand tracing and superimposition.

Methods

The institutional review board for the protection of human subjects reviewed and approved the research protocol (IRB-201626016).

A total of 28 pairs of pre-treatment (T_1) and post-treatment (T_2) lateral films were selected. The T_1 and T_2 lateral films were taken with the same X-ray machine. The subjects consisted of 21 females and seven males. The age for T_1 ranged from 12 to 27 years, with a mean age of 15.32 years; the T_2 ages ranged from 14 to 29 years, with a mean age of 18.03 years. The experimental design is shown in Fig. 1. Calibration rulers were used to control distortions and resolution errors during the printing and scanning process.

Landmark identifications

One operator identified landmarks on the T_1 and T_2 digital lateral films using customised software produced by Key Laboratory of Machine Perception. The landmarks identified include the upper reference point (URP), lower reference point (LRP), pterygoid point (Pt), posterior nasal spine (PNS), anterior nasal spine (ANS), subspinale (A), supramental (B), pogion (Pog), menton (Me), gonion (Go), condylion (Co), upper incisor edge (UIE), upper incisor apex (UIA), upper first molar mesial buccal cusp (UM), upper first molar mesial apex (UMA), lower incisor edge (LIE), lower incisor apex (LIA), lower first molar mesial buccal cusp (LM), and lower first molar mesial apex (LMA).

Superimposition methodology

The structural superimposition method developed by Johnston [27] for the anterior cranial base, maxilla and mandible was independently used by each operator.

Hand tracing superimposition

Three operators independently performed manual tracings of T_1 and T_2 side by side on acetate paper. Information from the hand superimposition was recorded using a similar method as that developed by the University of California, San Francisco[11]. A series of ten pinholes were drilled into T_1 films in the non-information-bearing area surrounding the anatomic region of interest. Four corner pinholes on the T_1 films were used to register the scanned hand tracings onto corresponding digital films. The other six pinholes on the T_1 films were used in pairs to register the between-film relationships onto T_2 tracings for the three types of hand tracing superimposition methods and to convert the between-film relationship of the hand superimpositions into a digital record by scanning. For the T_2 films, only the four corner pinholes were drilled. The lateral films with pinholes and the corresponding hand tracings were scanned (HP Color LaserJet 2840, Hewlett-Packard Company, Palo Alto, CA, USA). The operators identified the scanned pinholes that carried the information on superimposition and image size from the T_1 and T_2 tracings.

Automated superimposition

Figure 2a showed the rectangular area enclosed by landmarks on the anterior cranial base, maxilla and mandible was used to detect the keypoints. On the anterior cranial base, this area was defined by the URP, S, Pt and Na. On the maxilla, this area was enclosed by the Pt, PNS, ANS and A. On the mandible, this area was enclosed by the LM, Pg, Me and Go.

The OpenCV ORB feature was used only in the areas described above. The maximum keypoint number was fixed at 10,000. To increase the detection efficiency, we used the Features from Accelerated Segment Test(FAST) [28] algorithm. The basic principle of FAST is to determine whether the center pixel point(P) is a keypoint in a 16-pixel circumference circle (Bresenham circle with a radius of 3). If the brightness of N consecutive pixels(l_x) on the circumference is brighter than the brightness l_p of P plus a threshold t(l_x>l_p+t), or darker than the brightness l_p minus t(l_x<l_p-t), the center pixel point P was detected as a keypoint. Because the number of keypoints identified in most cases does not reach the fixed maximum, we set the FAST feature threshold as zero to increase the number of keypoints as much as possible. Each detected keypoint was described using a vector. Nearest-neighbour matches were discovered with brute-force Hamming distance of one keypoint vector on T_1 to each keypoint vector on T_2.

Considering that the ORB results might not be completely accurate, the Grid-based Motion Statistics for Fast, Ultra-robust Feature Correspondence (GMS)[26] algorithm was applied to filter the results of the previous matches. Specifically, we calculated the relative offset distances and rotation angles of the T_1 and T_2 cephalograms based on the feature matching results and counted the horizontal and vertical distances of each pair of successfully matched keypoints. All the matches were divided into two sets by the symbol based on the relative offset distance, and the set with a small number of matches was rejected as a successful match. When calculating the relative rotation angles of the two cephalograms, we randomly sampled two keypoints in T_1 and calculated the angle formed by the line connecting them and the horizontal direction; the corresponding angles in T_2 were also calculated. The difference between the two angles equalled the relative rotation angles of a pair of points. We sampled these pairs of points in T_1 until each corner point was sampled without repetition. Again, the opposite result of a small number of symbols was removed. After that, the final match of the T_1 and T_2 cephalograms was obtained. (The Feature matching algorithms were further displayed in Additional file 1)

Figure 2b demonstrates the flowchart of the automated superimposition process.

Calculation of T2 landmark distances

The T_1 digital films were used as templates to calculate T_2 cephalometric landmark linear distances (T_2LDs). In detail, to avoid landmark identification errors, the automatically superimposed T_2 films with identified landmarks were duplicated, and the corresponding T_2 hand tracings were registered on the duplicated films at four pinholes. The manual and automated tracings were superimposed together onto T_1 films on the superimposing pinhole on each side, and all the coordinate locations of the T_2 films were changed and documented accordingly. To test the inter-operator reliability of hand superimposition, T_2LDs between operators for three types of superimposing methods were measured (Fig. 3a). To evaluate the accuracy of automated superimposition, the average coordinate value for each cephalometric landmark among three manually traced T_2 films were set as the true values, and the differences in T_2LDs were calculated for each pair of superimposed manual and automated tracings (Fig. 3b).

Statistical methods

Statistical analyses were carried out with SPSS 25.0 (SPSS Inc., Chicago, IL, USA). Descriptive statistics were calculated for T_2LDs of multiple corresponding cephalometric landmarks for operative differences in manual and automated superimposition. To further examine the statistical accuracy of automated superimposition based on manual superimposition, a paired t-test was applied. P-values less than 0.05 were considered significant.

Results

The descriptive statistics for mean T_2LDs of hand structural superimposition on the anterior cranial base, maxilla and mandible between operators are listed in Table 1, Table 2, Table 3, respectively. In the anterior cranial base superimposition (Table 1), the T_2LD at the pterygomaxillary fissure showed the least difference (Ptm, 0.61 ± 0.63 mm), while the T_2LD at the menton showed the greatest difference (Me, 1.02 ± 0.96 mm). In the mandibular superimposition (Table 2), the T2LD at the condylion showed the greatest difference (Co, 1.65 ± 1.24 mm), and the least difference was observed for the LIE (0.62 ± 0.86 mm), followed by the other midline structures (LIA, 0.76 ± 0.55 mm; B point, 0.75 ± 53 mm; Pog, 0.75 ± 0.48 mm; and Me, 0.70 ± 0.45 mm). The operator differences in the maxilla were quite close between the landmarks (Table 3), ranging from 0.78 mm to 0.82 mm.

Table 1
Descriptive statistics for average T_2 landmark distance (mm) between operators and paired t-test for the accuracy between hand and automated superimposition with true values in cranial base superimposition.

	N	Operative difference (Hand process) (mm)		N	Accuracy (Hand process) (mm)		Accuracy (automated process)(mm)		P value
		Mean	SD		Mean	SD	Mean	SD	
Pt	84	0.61	0.63	28	0.33	0.28	0.41	0.37	0.128
PNS	84	0.69	0.65	28	0.40	0.32	0.47	0.39	0.290
ANS	84	0.82	0.76	28	0.47	0.38	0.54	0.45	0.313
A point	84	0.85	0.86	28	0.50	0.42	0.59	0.54	0.274
B point	84	0.99	0.94	28	0.58	0.46	0.59	0.48	0.880
Me	84	1.02	0.96	28	0.55	0.51	0.64	0.58	0.366
Go	84	0.91	0.88	28	0.52	0.43	0.48	0.50	0.626
Co	84	0.67	0.68	28	0.39	0.34	0.44	0.35	0.254

Table 2
Descriptive statistics for average T_2 landmark distance (mm) between operators and paired t-test for the accuracy between hand and automated superimposition with true values in maxillary superimposition.

	N	Operative difference (mm)		N	Accuracy (Hand process) (mm)		Accuracy (automated process) (mm)		P value
		Mean	SD		Mean	SD	Mean	SD	
PNS	84	0.79	0.60	28	0.47	0.25	0.56	0.44	0.189
ANS	84	0.82	0.64	28	0.56	0.37	0.57	0.44	0.855
A point	84	0.78	0.56	28	0.54	0.34	0.53	0.45	0.889
UIE	84	0.82	0.63	28	0.51	0.33	0.53	0.38	0.737
UIA	84	0.80	0.58	28	0.49	0.30	0.61	0.61	0.220
UM	84	0.78	0.59	28	0.48	0.27	0.50	0.40	0.718
UMA	84	0.80	0.60	28	0.49	0.35	0.51	0.43	0.763

Table 3
Descriptive statistics for average T_2 landmark distance (mm) between operators and paired t-test for the accuracy between hand and automated superimposition with true values in mandibular superimposition.

	N	Operative difference (mm)		N	Accuracy (Hand process) (mm)		Accuracy (automated process) (mm)		P value
		Mean	SD		Mean	SD	Mean	SD	
B point	84	0.75	0.53	28	0.41	0.25	0.47	0.26	0.254
Pog	84	0.75	0.48	28	0.41	0.22	0.49	0.23	0.059
Me	84	0.70	0.45	28	0.42	0.22	0.46	0.32	0.566
Go	84	1.38	1.21	28	0.74	0.49	0.72	0.39	0.836
Co	84	1.65	1.24	28	0.94	0.59	0.69	0.50	0.695
LIE	84	0.62	0.86	28	0.52	0.36	0.58	0.30	0.538
LIA	84	0.76	0.55	28	0.41	0.25	0.47	0.26	0.226
LM	84	1.00	0.77	28	0.52	0.33	0.58	0.29	0.401
LMA	84	0.87	0.63	28	0.46	0.28	0.52	0.28	0.288

The accuracy of multiple cephalometric landmarks generated by automated superimposition using three types of superimposition methods as determined by the paired t-test is shown in Table 1, Table 2 and Table 3. Hand superimposition showed slightly higher accuracy compared with that of paired automated superimposition. However, there were no statistically significant differences ($p > 0.05$) between the two operations in all selected cephalometric landmarks of interest. The accuracy of both methods demonstrated spatially related errors in superimposition on the anterior cranial base and mandible.

Discussion

Decades ago, researchers studying craniofacial growth in the presence of metallic implants advocated superimposing structures that are stable during growth[20–22], and structural superimposition has been demonstrated to be the most accurate technique[23, 24]. Although the validity of structural superimposition has been recognised worldwide, there are remaining issues. First, in some films with low quality or high complexity due to overlapping structures, it is impossible for orthodontists to determine a sufficient number of stable structures, especially in the maxilla and mandible. Second, if several stable structures do not fit appropriately in the same between-film position, the orthodontists must defer to their biological knowledge and practical experiences. Thus, the results may vary depending on the knowledge and understanding of the operators. Both of these limitations weaken the reliability of manual structural superimposition.

Landmark identifications are well accepted as the main source of cephalometric errors[15]. To avoid this type of error and focus mainly on the reliability and accuracy of superimposition, we carried out our study using film duplication and between-film registration techniques. As shown in Tables 1, 2 and 3, differences in manual superimposition between operators using three types of superimpositions varied greatly from 0.61 mm to 1.65 mm, a range that was greater than the intra-operator reliability reported by Huja et al.[3] This finding suggests that the inter-operator variability of superimposition is an important variation of results. In our study, we infer that rotational effects produced a greater number of errors than those produced by translational effects on the superimposition of the anterior cranial base and mandible, which were similar to the results provided by Baumrind et al. [2] and Cook et al.[6]. However, we also found that the mean T_2LDs of the six landmarks in the maxillary superimposition were quite similar to each other without showing a progressive trend from any centre. This observation suggests that the translational error may have been the predominate cause of error in maxillary superimposition.

The differences in accuracy between manual and automated superimposition are smaller than the variability among operators but also demonstrate a similar increase in error tendency with spatial patterning on the anterior cranial base and mandibular superimpositions. Although slightly higher accuracy errors were observed on the automated superimpositions, there were no significant differences in accuracy between the two methods in comparison with the differences in accuracy between the true values determined by the paired t-test. This finding suggests that compared with hand tracing, automated superimposition does not lead to a significantly increased error of accuracy and has the great advantages of absolute consistency and time-efficiency. Taken together, these three points suggest that the automated superimposition is comparable to the traditional hand tracing process and can replace the latter.

In comparison with superimposition on single reference planes, structural superimposition on stable regions provides more constraint conditions. The integral feature matching alogrithms[25, 26, 28] that identify pixel keypoints in a weak texture environment within regions limited by landmarks containing mainly stable structures and superimpose T_1 and T_2 cephalograms by matching pairs of identical or similar keypoints are tested to be accurate. However, a considerable number of high-quality keypoints would favour better accuracy, which relies on the distinction of stable structures from other structures by a sharp contrast in pixel intensity. An improvement in image resolution, especially on the inner bony structures, along with advancement of the sensitivity for keypoint detection, would solve the problems of this technique.

As discussed above, these three kinds of superimposition show similar patterns of error to those shown by traditional manual processes reported by Baumrind et al. [2] Based on the proven accuracy of automated superimposition in the three kinds of superimposition, this method is comparable to the traditional hand tracing process and can replace the latter. In a clinical perspective, prediction of treatment changes is still challenging because of the time-consuming and accuracy questionable procedure of manual cephalometric superimposition when a considerable number of cases are required for statistical analysis, this automated method could be considered as the beginning of big data analysis using digital cephalograms.

Conclusions

Computer-aided cephalometric superimposition provides comparable results to those of traditional hand tracing when structural superimposition is concerned. With the help of proper software, this method for digital filmless cephalometry will provide a powerful tool for academic research in the era of digital cephalograms and big data.

Abbreviations

ORB:Oriented FAST and Rotated BRIEF; T_1:pre-treatment; T_2:post-treatment; URP:upper reference point; LRP:lower reference point; Pt:pterygoid point; PNS:posterior nasal spine; ANS:anterior nasal spine; A:subspinale; B:supramental; Pog:pogion; Me:menton; Go:gonion; Co:condylion; UIE:upper incisor edge; UIA:upper incisor apex; UM:upper first molar mesial buccal cusp; UMA:upper first molar mesial apex; LIE:lower incisor edge; LIA:lower incisor apex; LM:lower first molar mesial buccal cusp; LMA:lower first molar mesial apex; FAST:Features from Accelerated Segment Test; GMS:Grid-based Motion Statistics for Fast, Ultra-robust Feature Correspondence; T_2LDs:T_2 cephalometric landmark linear distances;

Declarations

Ethics approval and consent to participate

The institutional review board for the protection of human subjects reviewed and approved the research protocol (IRB-201626016). Clinical trial registration number: ChiCTR1800017694; Public title: Growth and compensatory of dental maxillofacial affected by orthodontic treatment, computer-aided diagnosis and prediction: a retrospective study of X-ray data of a large sample of orthodontic patients

Consent for publication

Not applicable.

Availability of data and materials

The full datasets used and analyzed during the current study are available on reasonable request from the corresponding authors at tmxuortho@163.com and kqbinghan@bjmu.edu.cn.

Competing interests

The authors declare that they have no competing interests.

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Authors' contribution

Contribution to conception and design: JYR, SGY, YXN, DYB, LQF, LSQ, HB and XTM;

Contribution to data acquisition and interpretation: JYR and SGY;

Contribution to performance of all statistical analyses: JYR;

Contribution to drafting of manuscript: JYR and DYB;

Contribution to critical revision of manuscript: SGY, YXN, LQF, LSQ, HB and XTM

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Figures

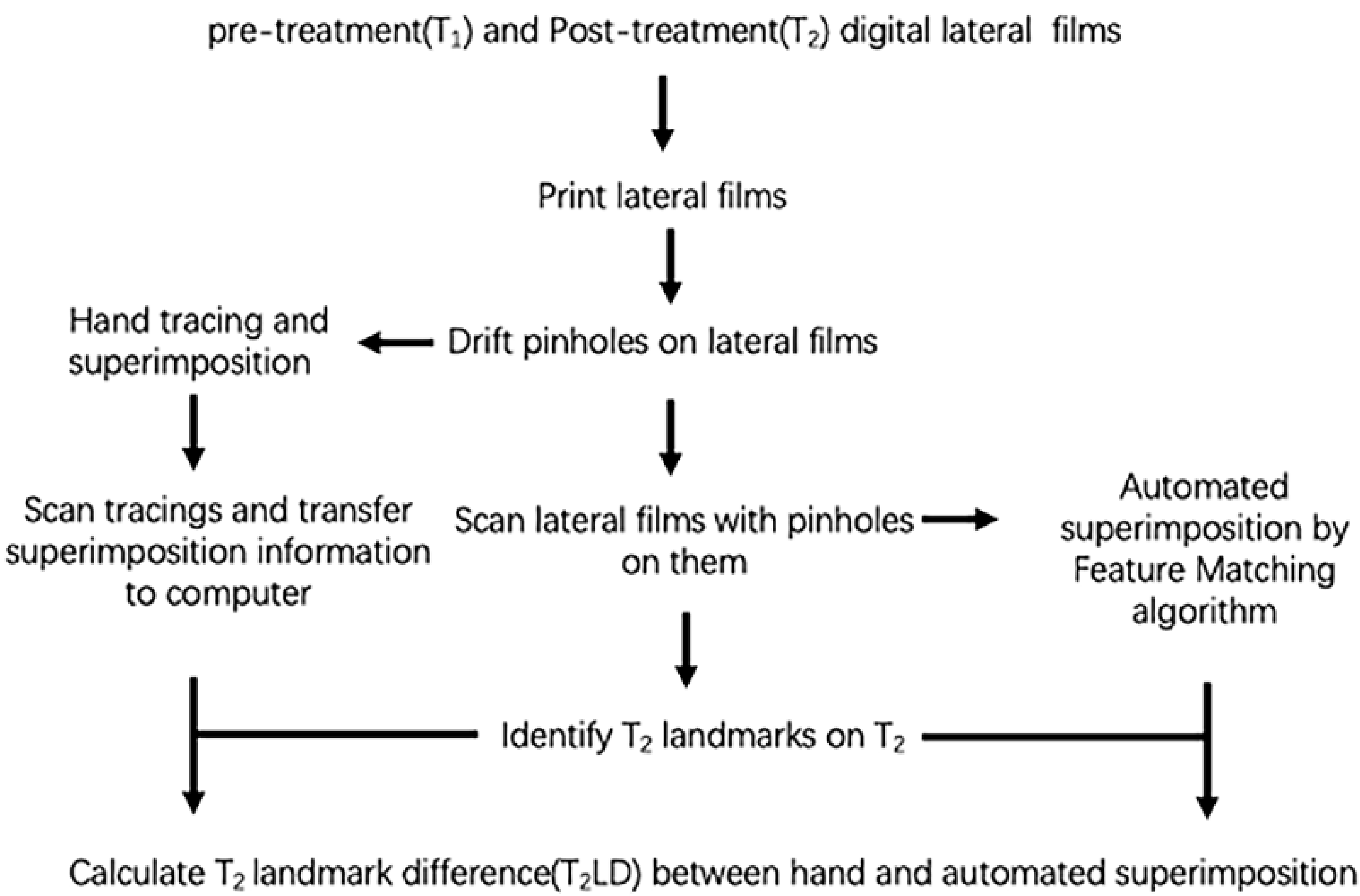

Figure 1

Schematic flowchart of the experimental design.

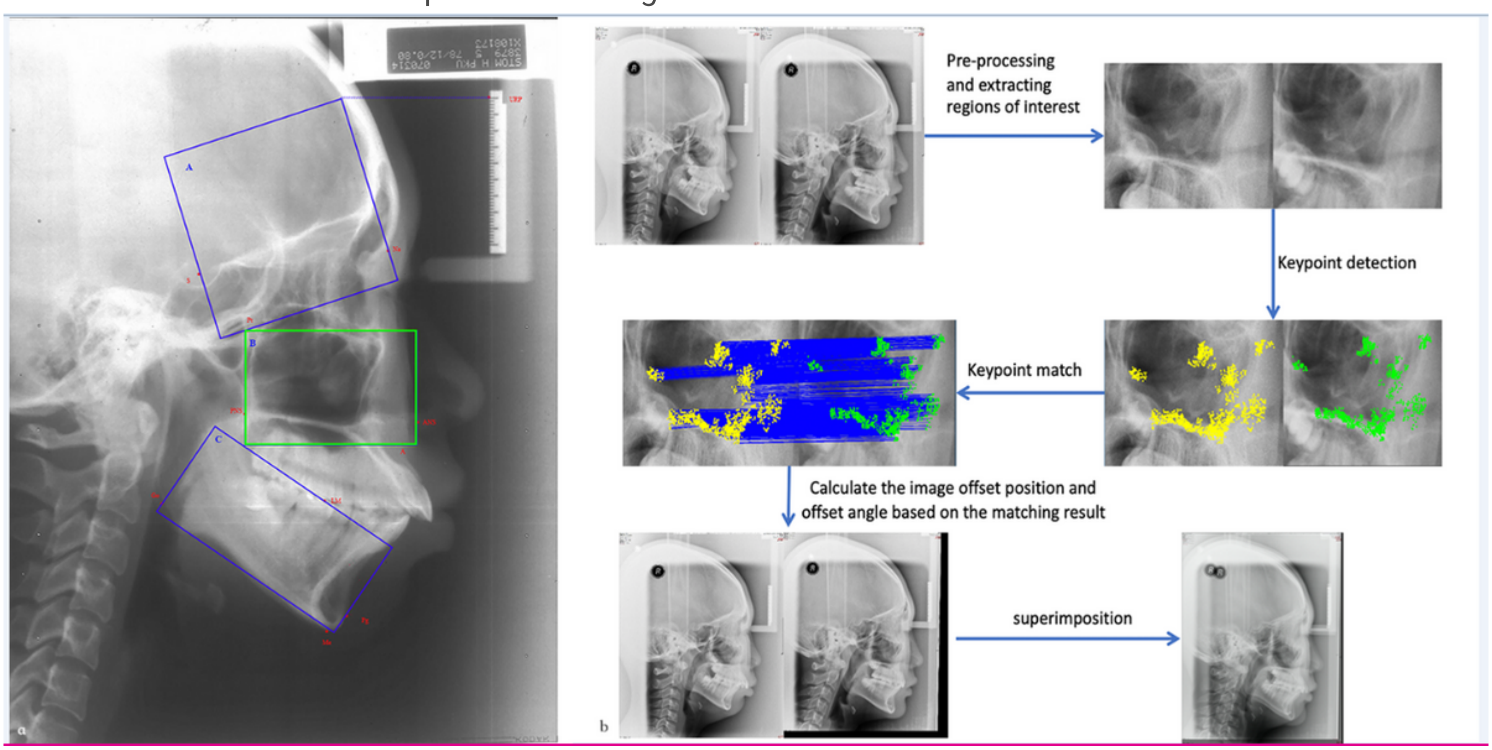

Figure 2

a. The rectangular area mainly consisting of stable structures were used to detect keypoints enclosed by landmarks on the anterior cranial base, maxilla and mandible. A. Area on the Anterior cranial base: URP-S-Pt-Na. B. Area on the maxilla: Pt-PNS-ANS-A. C. Area on the mandible: LM-Pg-Me- Go. b. Keypoint detection within the confined area in the anterior cranial base, maxilla and mandible and superimposition of T2 cephalograms on T1. The figure is an example of the process in maxilla.

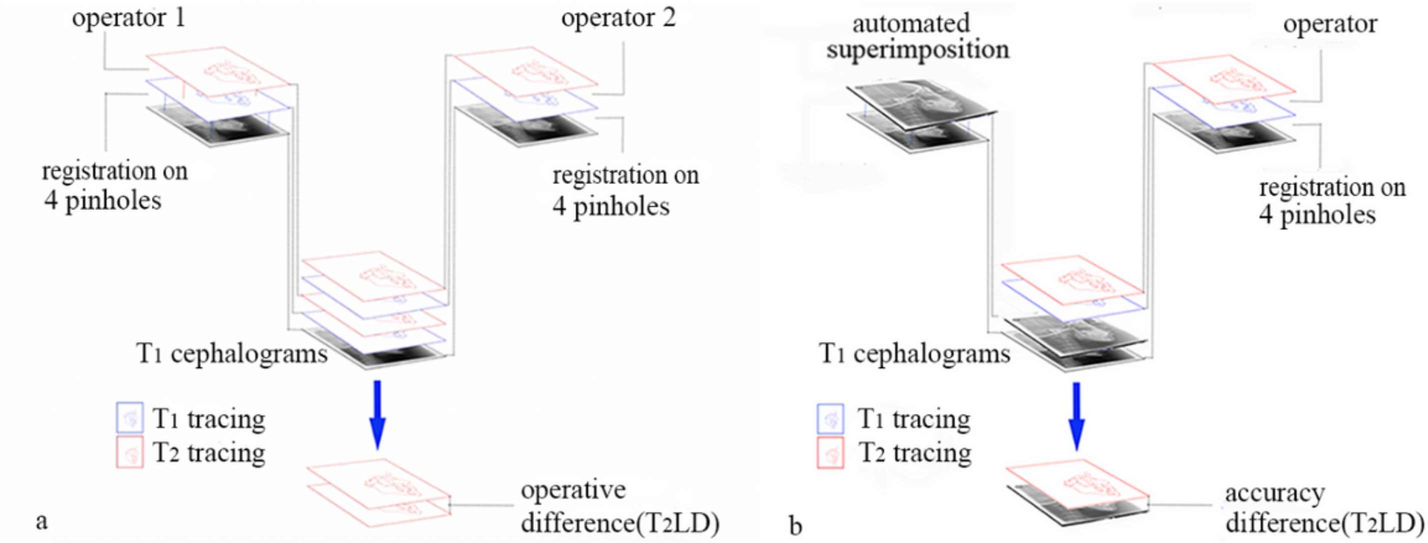

Figure 3

a. Pairwise T2LD for manual superimposition between different operators. b .Pairwise T2LD for manual and automated superimposition with true values, respectively.