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A New Innovative Software to Automatically Outline Condyles In Orthopantomography

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Abstract

Purpose: To evaluate the variation in morphology of the TMJ condyles in orthopantomogram (OPG) images using the BoneFinder® software.

Material and methods: The study included radiographic assessment of 200 condyles from 100 digital OPGs. The outline of the condyles was computed using BoneFinder®. Statistical shape models were built to calculate the most prevalent shape as well as the variation in shape according to sex and side (right and left). A fully automatic BoneFinder® TMJ system to analyze the condyles in new, unseen images was generated and evaluated.

Results: The main mode of variation across all subjects was between an elongated oval shape and a flattened round condyle shape. The second mode of variation was between the condyle being crooked and showing a bulge. There was no significant correlation between any of the first five shape modes and either sex (using Pearson correlation analysis). The left and right condyles of an individual were highly symmetric. The fully automatic BoneFinder® system achieves high accuracy in automatically outlining the condyles in OPG images.

Conclusion: BoneFinder® may be a useful tool for the diagnosis and prognosis of various disorders involving the TMJ condyles.

Keywords: Temporomandibular joint, condylar shape, BoneFinder®, Statistical Shape Model, automatic image analysis.

Introduction

The temporomandibular joint (TMJ) is a unique joint comprising of glenoid fossa and articular eminence superiorly and condyle inferiorly. Physiologically, the morphology of the TMJ condyles differs among individuals, with age, sex, masticatory force, habits and facial types.[1,2] Further changes in the mandibular condyle occur in various disease conditions. Several classifications of condylar shapes have been described based on radiographic, cadaveric, dry mandible and intra-operative evaluation. Outlining the bone contours in radiographs plays an important role in disease diagnosis, pre-operative planning and treatment analysis. Among the various radiographic techniques currently available to measure the TMJ, the most commonly used radiographs are orthopantomograms (OPGs). The latter are usually preferred due to their easy availability, accessibility, low radiation exposure and low cost. They also enable comparison of right and left condyles in a single film.

At present, the most common method for analyzing condylar shape using conventional radiographs is manual qualitative analysis. However, this is time-consuming, tedious and produces inconsistencies. There are also concerns about the intra-observer and inter-observer reliability when evaluating condylar morphology.[3] To overcome these difficulties, a software system, BoneFinder® (www.bone-finder.com), has been developed to map the condylar morphology automatically. This eliminates the limitations associated with manual analysis and provides accurate automatic measurements.

BoneFinder® is a software system that uses a statistical model (derived from training examples of images with associated point positions) to automatically locate points on the outline of target structures in new images. Given a set of OPG images with the condyle point positions for each, a fully automatic structure-specific BoneFinder® system was generated.

This study was designed to evaluate the condylar shape in OPGs using the BoneFinder® TMJ system.

Material and methods

Dataset

The study included 200 condyles from 100 digital OPGs (33 males, 67 females) from an Indian population. Digital radiographs of patients aged 18 to 45 years, without TMJ disorders were included in the study. Exclusion criteria were patients with TMJ disorders. The OPGs were digitally calibrated to 1:1 ratio.[4] Approval for this study has been obtained from the Institutional Review board (SRMU/M&HS/SRMDC/2017/F/002). The study was done in accordance with STROBE guidelines.

Software system

BoneFinder® is a software system to automatically outline skeletal structures in 2D radiographs by placing a number of points along the bone contour or at key landmark positions. The system follows a machine learning approach. Given some training data (images and point positions) it learns to identify the same point positions in new unseen images.[5, 6] The system has previously been used for the assessment of skeletal structures such as the hips, knees or hands. In this work, the BoneFinder® system was modified to detect and outline the TMJ condyles in OPG images.

The manual ground truth point positions for training an automatic BoneFinder® TMJ system were generated by applying the following steps in BoneFinder®:

- For each condyle, four key points were identified and placed. The point positions were as follows (Fig 1):

- Point 0 was placed on the anterior surface of condyle just below the maximum convexity.
- Point 1 was placed opposite from point 0 such that it was perpendicular to the axis going through the joint (red line).
- Point 2 was placed about halfway between point 0 and point 1.
- Point 3 was placed below point 0 such that the distance between points 0 and 2 is approximately the same to the distance between points 0 and 3.
- Equally spaced points were placed in-between the key points along the contour of the bone to capture the shape of the condyle with 32 points (Fig 2).

A structure-specific BoneFinder® TMJ system was generated using the manual point positions of both sides for each image (where the right TMJ was mirrored to appear as a left TMJ). To analyze the performance of the fully automatic BoneFinder® TMJ system in outlining the condyles in OPG images, two-fold cross-validation experiments were performed (the system was trained on 2 sides of 50 subjects and then tested on the 2 sides of the remaining 50 subjects, and then training/testing was repeated with the datasets switched; results were averaged over the two runs). To evaluate the performance of the system, the results of running the automatic BoneFinder® TMJ system were compared to the manual annotations (i.e. point positions). Results are reported in both pixels and as a percentage of a reference length defined by the distance between points 3 and 28 (Fig 3, red points).

Shape analysis

BoneFinder® uses Statistical Shape Models (SSMs) to describe the shape of each condyle based on all 32 point positions. SSMs enable studying shape distributions within and across populations, where shape describes all geometric information of an object disregarding location, orientation and scale of the data.[7] SSMs, therefore, provide a means to quantitatively describe the overall shape/morphology of a skeletal structure by identifying the directions of shape variation across a given dataset. To generate an SSM, all shapes are aligned and Principal Component Analysis is applied to identify the main modes of variation across the dataset, ordered by the variance they explain (largest first).[8] The first SSM mode gives the main direction of shape variation; the second SSM mode gives the second most prevalent direction of shape variation, etc.

The following TMJ condyle characteristics were analyzed using SSMs generated from the manual ground truth annotations (i.e. point positions);

1. The most prevalent shape;
2. Shape peculiar to sex; and
3. The degree of symmetry between left and right side.

Results

Shape analysis

The full SSM (n=100, two sides each) showed that five SSM modes explained 95% of the overall shape variation, and eight modes explained 98% of the overall shape variation. Fig 4 shows the shape variation for each of the eight modes where red gives the mean shape and the blue/green curves represent +/-2.5 standard deviations. The main mode of variation across all subjects was between an elongated oval shape and a flattened round condyle shape. The second mode of variation was between the condyle being crooked and showing a bulge.

Sex analysis

A female SSM (n=67, two sides each) and a male SSM (n=33, two sides each) were constructed (Fig 5 & 6). Overlaying the SSM mean shape of the female and male models did not show any visible differences between sexes (Fig 7). For the female SSM, five modes explained 95% of shape variation, and nine modes explained 98% of shape variation. For the male SSM, five modes explained 95% of shape variation, and eight modes explained 98% of shape variation. The first five SSM modes suggest that the variation across males and females is very similar but that there are some small differences in the extent of variation per mode. The general tendency of shape variation in terms of different classes was consistent across sexes. The first shape mode explained significantly more of the shape variation in males than in females. Pearson correlation analysis showed no significant correlation between any of the first five SSM modes and either sex (Table 1).

Symmetry analysis

A left SSM (n=100) and a right SSM (n=100) have been constructed. Overlaying the SSM mean shape of the left and (reflected) right models did not show any visible differences (Fig 8). The shape variation between the left and right sides per subject was small compared to the overall shape variation in the dataset (Fig 9). The mean point-to-curve distances between the left and (reflected) right manual ground truth annotations of each subject were 3.1 pixels for the median, 6.0 pixels for the 90%ile, and 8.0 pixels for the 95%ile. That is, for 95% of all images the average distance between the overlaid left and right side point annotations was 8 pixels (averaged over all points). Expressing these distances as a percentage of the reference length (Fig 3, red points) gives 2.4% for the median, 5.4% for the 90%ile, and 5.7% for the 95%ile. The analysis reveals that the left and right condyles of an individual are highly symmetric.

Fully automatic search results of the BoneFinder® TMJ system

The fully automatic BoneFinder® TMJ system achieved a mean-point-to-curve distance of 1.1 pixels for the median, 3.6 pixels for the 90%ile, and 5.7 pixels for the 95%ile based on two-fold cross-validation experiments. Expressing these errors as a percentage of the reference length (Fig 3, red points) gives 0.9% for the median, 2.7% for the 90%ile, and 4.3% for the 95%ile. This analysis shows that the BoneFinder® TMJ system is highly accurate in automatically outlining the TMJ condyles in OPG images.

Discussion

There has been continuous research in analyzing condyle morphology in both normal and pathological conditions such as internal derangement, osteoarthritis, dislocation of TMJ etc. Assessment of TMJ condyle morphology is required for diagnosing pathological changes, treatment planning, treatment follow up and forensic science.

TMJ condylar shape analysis can be carried out using dry skull, cadaver and or in an intraoperative assessment setting. The morphology of the TMJ condyles can also be visualized and assessed using imaging modalities such as OPG, lateral cephalogram, TMJ tomogram, MRI, computed tomogram and cone beam computed tomogram.[9, 10]

OPG images have been chosen for this study as it is one of the most commonly used imaging modality for diagnostic purposes in the field. The benefits are the low radiation exposure and low cost compared to CT and CBCT, as well as the highly repeatability and wide availability .[11, 3] Furthermore, OPG images show both condyles in a single image.

The BoneFinder® TMJ system which has been evaluated in this study automatically and accurately outlines the TMJ condyles. This significantly reduces the time required for analyzing the shape of the condyle. BoneFinder® is a machine-learning system that learns from manually annotated data what to look for and then outlines the structure of interest in new unseen images automatically. This is useful for applying the system to additional images and new datasets – without the need for manual annotations. An overview of the steps involved in using BoneFinder® for automatic shape analysis is given in Fig 10.

Findings of this study vs other studies

The shape of the TMJ condyle is very variable even in individuals with no temporomandibular joint disorders. In numerous studies the morphology of TMJ condyles has been described and classified. The first reported evidence of classifying the condylar shape of the temporomandibular joint was by Yale et al. in the year 1961 using laminagraphic cephalometry; classifying the shape into convex, concave and flat .[12] A study in 2016 was done on 400 condyles using OPG images to find the most prevalent condyle morphology in the Indian population; identifying oval, bird beak, diamond and crooked finger condylar shapes, with oval-oval being the most common and crooked/crooked finger being the rarest shapes found .[11] Our study revealed that the elongated oval and flattened round shape of the condyle are the most prevalent shapes in the Indian population.

The condyle undergoes constant remodeling throughout life; the initial stages of growth of the condyle take place by intramembranous ossification, later on remodeling occurs by endochondral ossification. In the course of normal functioning of the TMJ, alteration in the shape of the condyle occurs due to balanced resorption and apposition such that the “normal” shape of the condyle is maintained. In contrast, there is more resorption than deposition of bone in diseased subjects which results in pathological alterations of the condyle. A radiographic study using submentovertex views has demonstrated an increase in the width of the condyle with increasing age .[2]

Shape of the condyle in TMJ disorders

Internal derangement of the TMJ is the most frequent disease affecting the joint. In this case, a convex and round appearance of the condyle is observed in anterior disc displacement with reduction .[13] Dislocation of the TMJ occurs when the condyle comes out of the fossa and stays in front of the articular eminence. Small round condyles are most prone for central dislocation .[14] Osteoarthritis is a clinical condition where degeneration of the joint components occurs. The commonest findings relating to osteoarthritis are a flattening of the condyle, erosions and osteophytes .[15]

Study outcome

The results of this study suggest that the BoneFinder® TMJ system may be used for clinically evaluating the shape of the TMJ condyles. Automatically locating the condyles and assessing their morphology provides the opportunity for automated risk factor assessment in TMJ conditions such as osteoarthritis, internal derangement and dislocation. Automatically outlining the condyle shape may also help in identifying age and sex of autopsy specimens in forensic odontology. For alloplastic total joint reconstruction, analyzing TMJ condyle morphology across subjects provides a basis for the shape variation present in a given population. The latter can be used to identify a suitable shape for reconstruction.

Merits of the study

BoneFinder® fully automatically maps the skeletal structure of interest from a 2D radiograph, which is the most commonly prescribed x-ray for most musculoskeletal disorders. This enables converting image data into useful medical information. Compared to using standard geometric measurements (e.g. length and angles) or the qualitative analysis of shape variation, SSMs have the advantage of describing the overall shape of the object while also being objective (i.e. reducing the subjective factor that often affects qualitative shape analysis). Our results demonstrate that the BoneFinder® TMJ system is highly accurate in outlining the TMJ condyles.

Fully automatic image analysis and SSMs have not been applied to analyze the shape of the TMJ condyles before. One of the main benefits of SSMs is that they can be used to quantitatively describe the shape. This enables, for example, statistical association analyses to identify whether there is any association/correlation between any of the SSM model modes and some other variable in the data (e.g. age, sex, disease status). In this study, SSMs were used to analyze (i) the most prevalent shape; (ii) any sex specific shape; and (iii) the degree of symmetry between the right and left sides.

Limitations

The BoneFinder® software requires training using suitable images and point annotations to generate a structure-specific system. The system evaluated in this work was trained using only 50 subjects (2-fold cross-validation experiments using 2 sides per image). Experiments from other skeletal structures suggest that the automatic search performance will significantly improve if more training data was included, ideally 300+ subjects. Future work will include the above performance analyses using a larger training dataset.

While in this study all condylar shape and symmetry analyses were done using the manually generated ground truth, the goal is to develop a BoneFinder® TMJ system that accurately and robustly identifies all point positions such that future SSM shape analyses can be conducted automatically.

Future perspectives

The presented results describe the first phase of the study which used 100 OPG images to analyze the accuracy of using the BoneFinder® system, as well as the most prevalent TMJ condyle shapes and the symmetry of the TMJ condyles between both sides of an individual.

The second phase of this study will include more training data to further improve the fully automatic search performance of the BoneFinder® TMJ system. Future work will also include (i) the exploration of automatic classification into previously qualitatively identified condyle shape subgroups; (ii) the inclusion of more subjects into the shape analysis; and (iii) the investigation of correlation between shape and age. The automatically identified point positions from the BoneFinder® TMJ system can also be used for comparative studies between normal subjects and subjects with TMJ disorders to identify shape differences that might be clinically relevant. Systemic conditions such as rheumatoid and psoriatic arthritis sometimes first manifest in TMJ by an altered condylar morphology. There is the potential that this could be identified using automatic shape analyses as described above.

In conclusion, BoneFinder® is an effective software system for assessing condylar morphology and may be used for diagnostic and prognostic purposes.

Please contact the authors to discuss assess to the BoneFinder® TMJ system for research purposes.

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Legends Tables and Figures

Table 1- **Sex analysis:** Correlation analysis between first five shape modes and sex

Number of tests per sex:	5				
p- value for significance:	0.010				
Number of samples:	200				
	Mode 1	*Mode 2*	*Mode 3*	*Mode 4*	*Mode 5*
Correlation with sex:	-0.0733	-0.0518	0.0654	-0.0103	-0.1259
p- value for sex:	0.3025	0.4667	0.3578	0.8854	0.0758

Figures

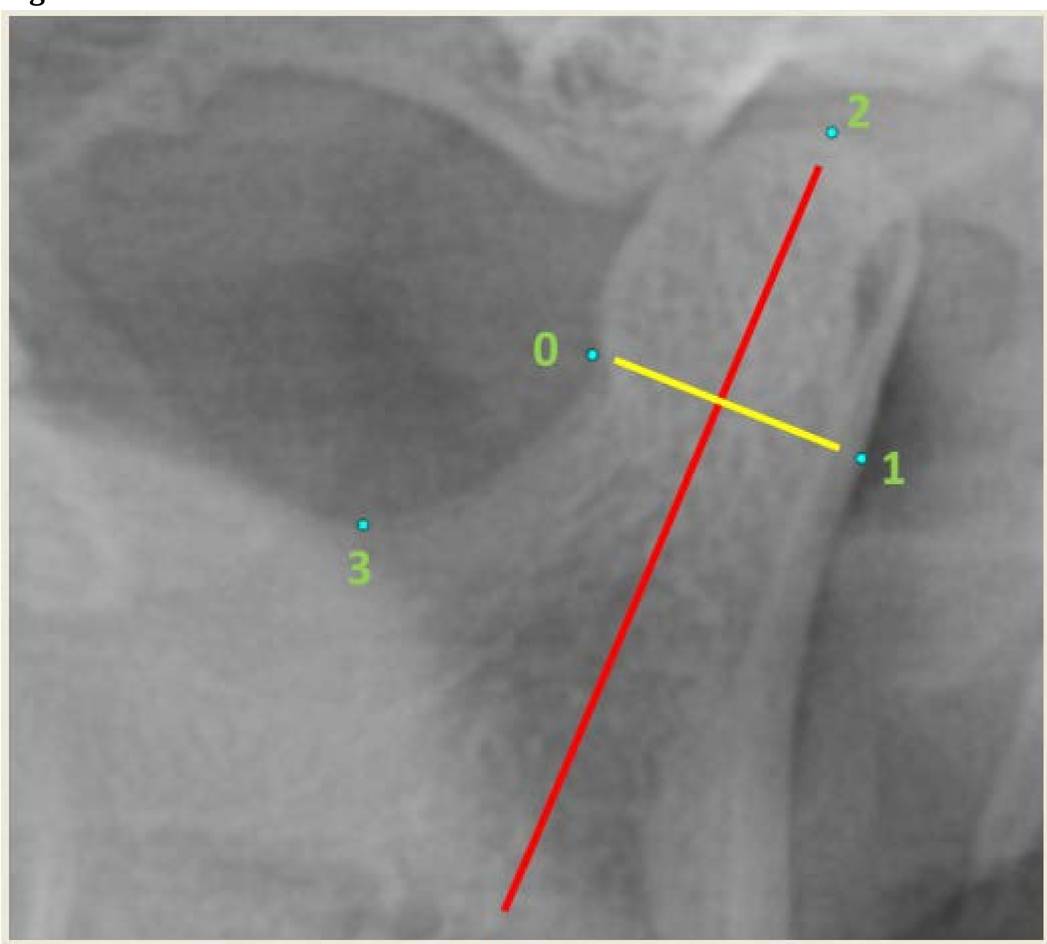

Fig 1: Initial key points for manual ground truth annotations.

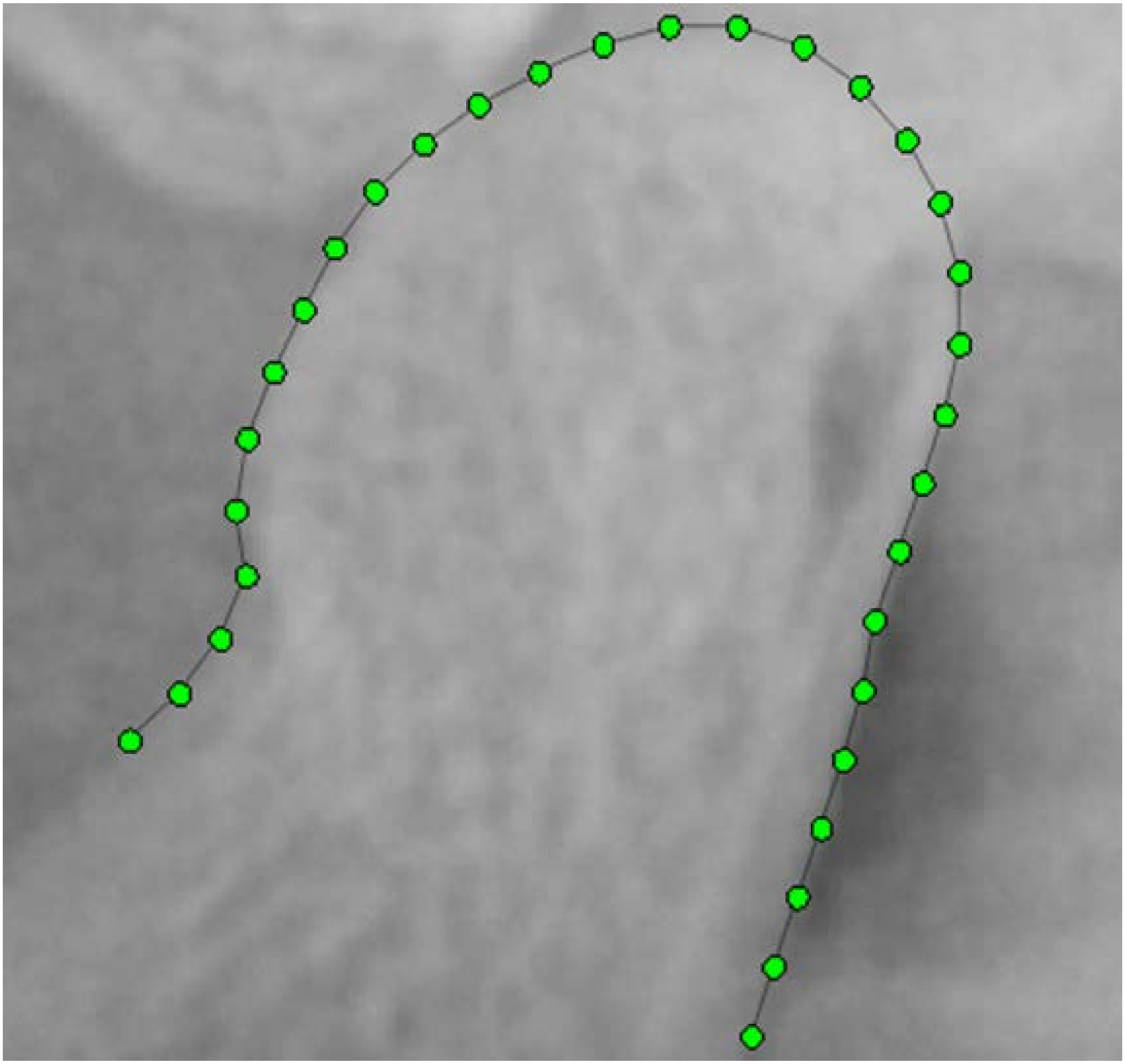

Fig 2: Dense ground truth annotation example (32 points).

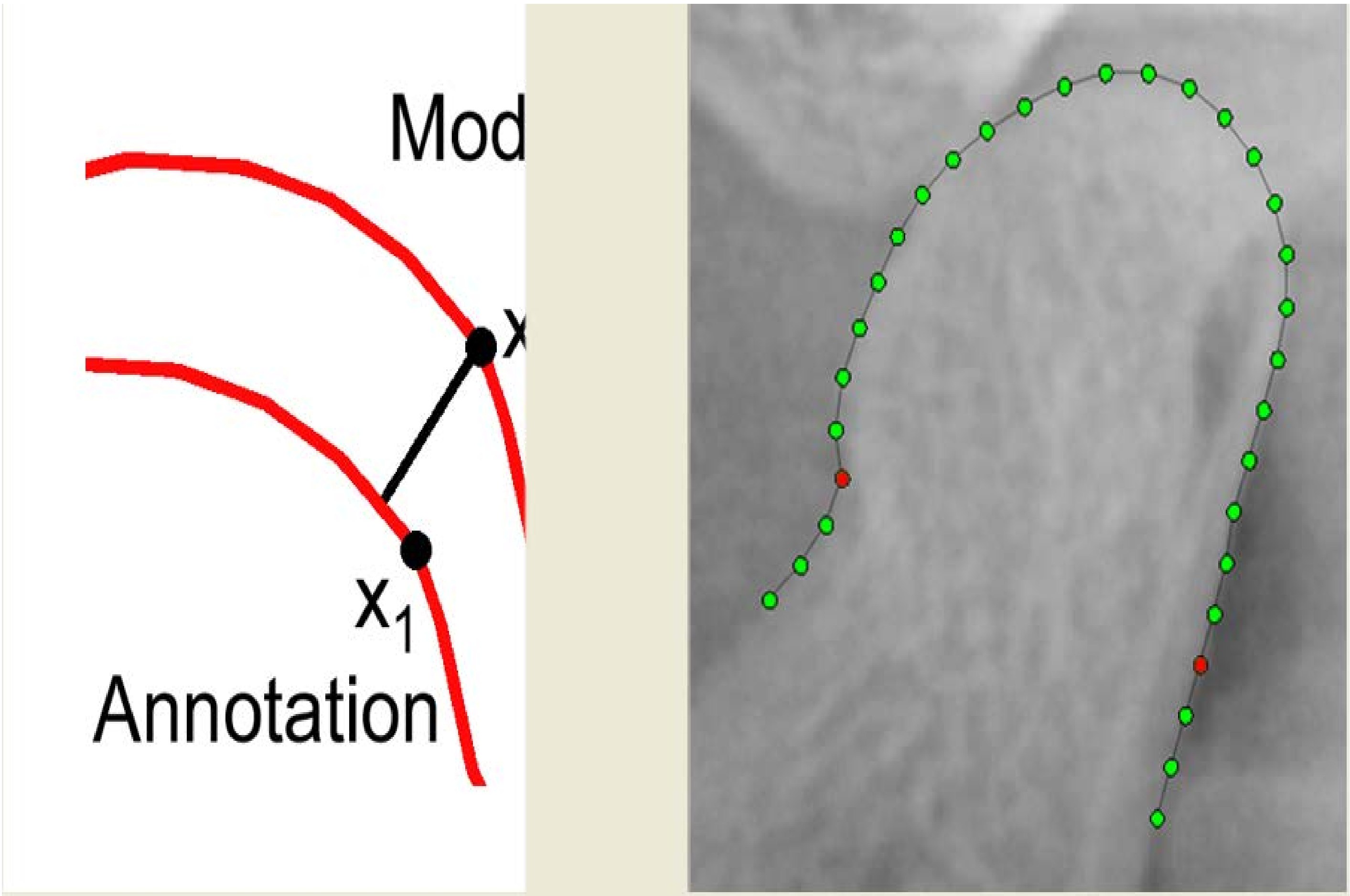

Fig 3: Point-to-curve distance definition (left) and reference length points (right, red points) used for evaluating the fully automatic search results of the BoneFinder® TMJ system.

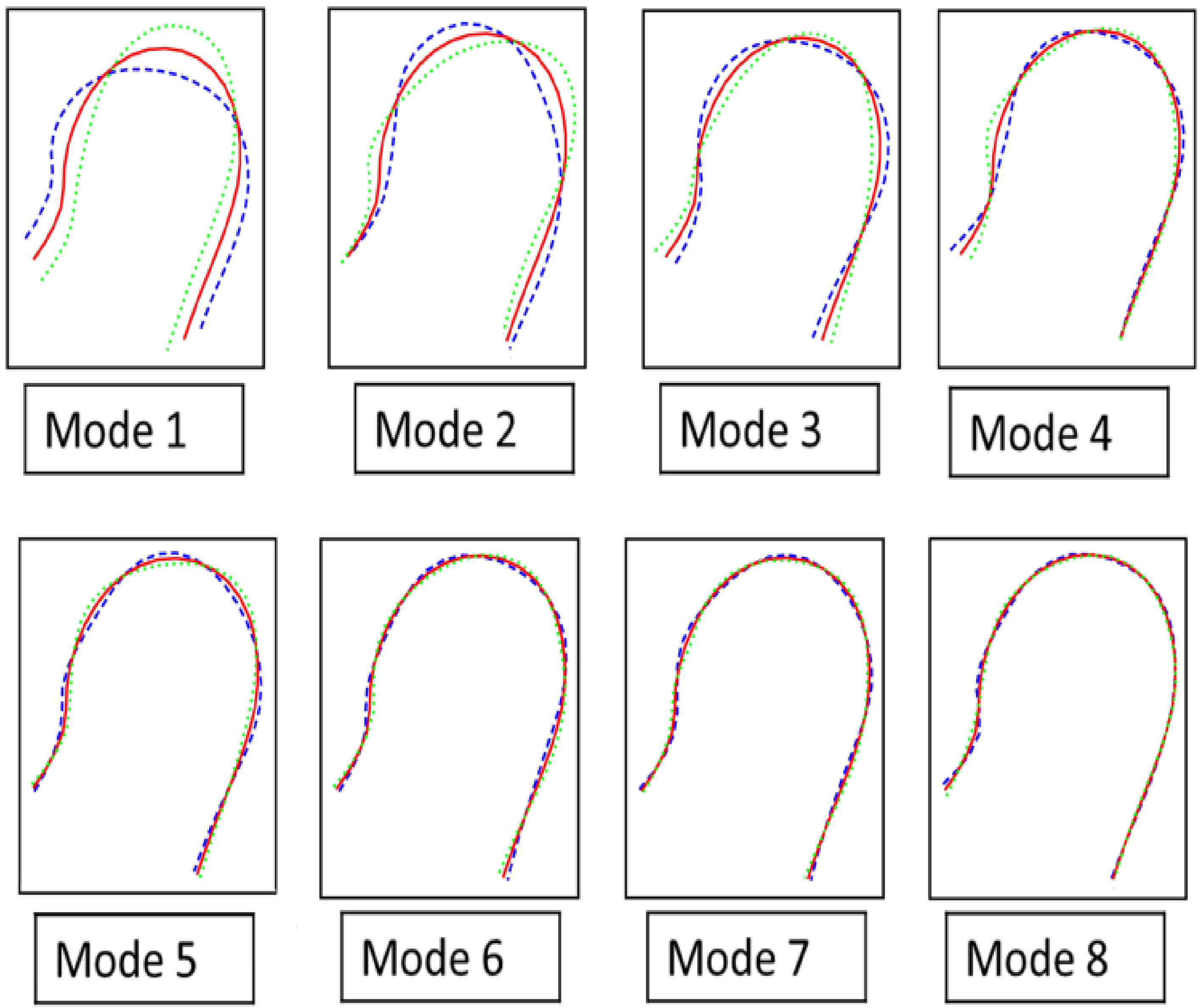

Fig 4: First eight SSM modes of variation of the full shape model (n=100, two sides each) which explain 98% of the overall shape variation. Each drawing shows the mean (solid line) ± 2.5 SD (dotted and dashed lines).

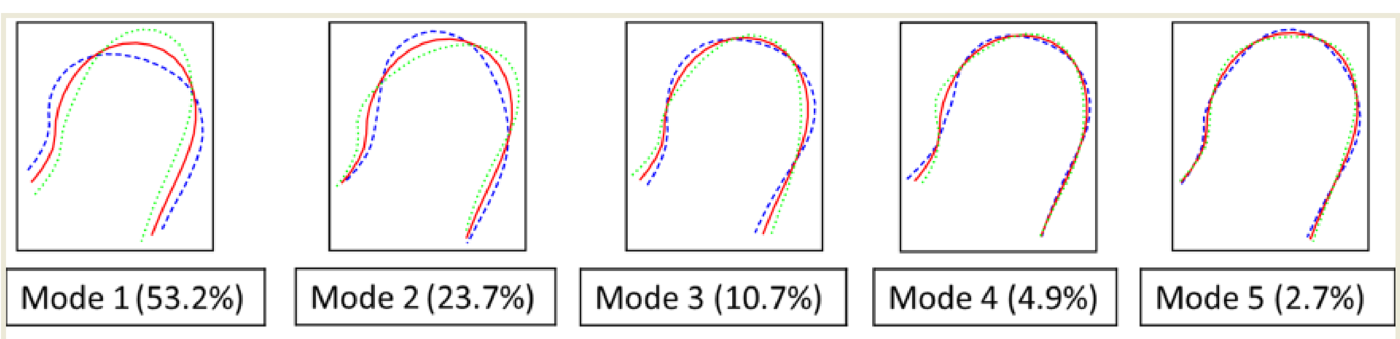

Fig 5: First five SSM modes of variation of the female shape model and the amount of shape variation explained per mode (n=67, two sides each); all five modes together explain 95% of the overall female shape variation. Each drawing shows the mean (solid line) ± 2.5 SD (dotted and dashed lines).

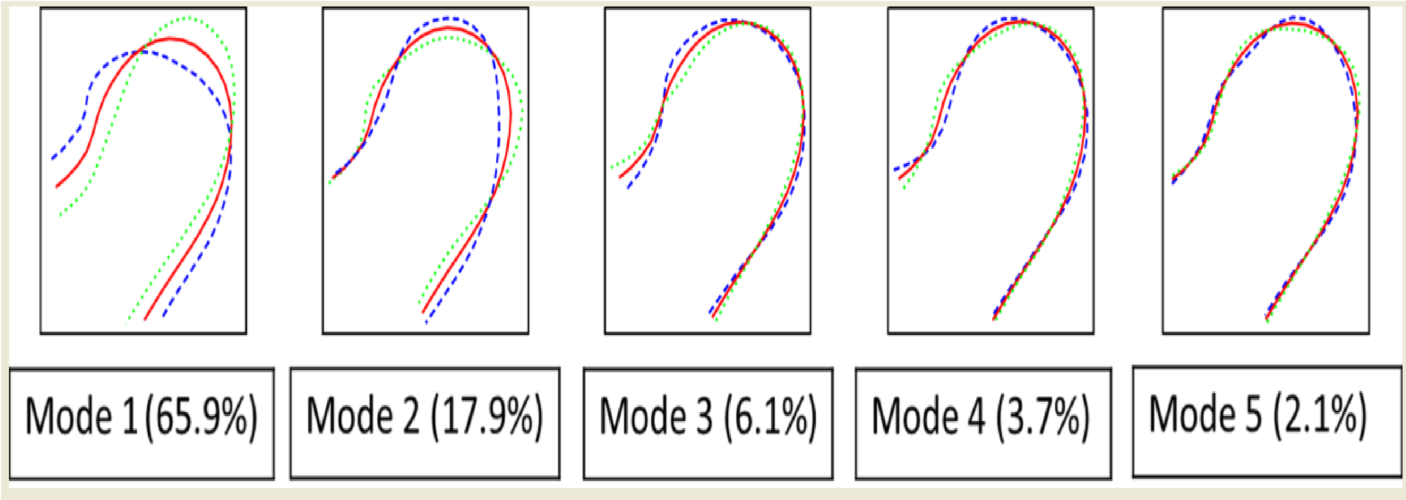

Fig 6: First five SSM modes of variation of the male shape model and the amount of shape variation explained per mode (n=33, two sides each); all five modes together explain 95% of shape variation. Each drawing shows the mean (solid line) ± 2.5 SD (dotted and dashed lines).