Review Article

Automatic Cephalometric Analysis

A Systematic Review

Rosalia Leonardi[a]; Daniela Giordano[b]; Francesco Maiorana[c]; Concetto Spampinato[d]

ABSTRACT

Objective: To describe the techniques used for automatic landmarking of cephalograms, highlighting the strengths and weaknesses of each one and reviewing the percentage of success in locating each cephalometric point.

Materials and Methods: The literature survey was performed by searching the Medline, the Institute of Electrical and Electronics Engineers, and the ISI Web of Science Citation Index databases. The survey covered the period from January 1966 to August 2006. Abstracts that appeared to fulfill the initial selection criteria were selected by consensus. The original articles were then retrieved. Their references were also hand-searched for possible missing articles. The search strategy resulted in 118 articles of which eight met the inclusion criteria. Many articles were rejected for different reasons; among these, the most frequent was that results of accuracy for automatic landmark recognition were presented as a percentage of success.

Results: A marked difference in results was found between the included studies consisting of heterogeneity in the performance of techniques to detect the same landmark. All in all, hybrid approaches detected cephalometric points with a higher accuracy in contrast to the results for the same points obtained by the model-based, image filtering plus knowledge-based landmark search and ''soft-computing'' approaches.

Conclusions: The systems described in the literature are not accurate enough to allow their use for clinical purposes. Errors in landmark detection were greater than those expected with manual tracing and, therefore, the scientific evidence supporting the use of automatic landmarking is low.

KEY WORDS: Cephalometry; Automatic; Computer-assisted; Points; Accuracy

INTRODUCTION

Since Broadbent[1] and Hofrath[2] introduced the cephalometer in 1931, cephalometric analysis has contributed to the analysis of malocclusion and it has become a standardized diagnostic method in orthodontic practice and research.[2–4]

Two approaches may be used to perform a cephalometric analysis: a manual approach, and a computer-aided approach. The manual approach is the oldest and most widely used. It consists of placing a sheet of acetate over the cephalometric radiograph, tracing salient features, identifying landmarks, and measuring distances and angles between landmark locations.

The other approach is computer-aided. Computerized cephalometric analysis uses manual identification of landmarks, based either on an overlay tracing of the radiograph to identify anatomical or constructed points followed by the transfer of the tracing to a digitizer linked to a computer, or a direct digitization of the lateral skull radiograph using a digitizer linked to a computer, and then locating landmarks on the monitor.[5–7] Afterwards, the computer software completes the cephalometric analysis by automatically measuring distances and angles.

The evolution from full manual cephalometrics to computer assisted-cephalometric analysis is aimed at improving the diagnostic value of cephalometric analysis by reducing errors and saving time. Errors in

[a] Associate Professor, Department of Orthodontics, University of Catania, University of Catania, Catania, Italy.
[b] Associate Professor, Department of Computer Engineering, University of Catania, University of Catania, Catania, Italy.
[c] Engineer Research Assistant, Department of Informatics, University of Catania, University of Catania, Catania, Italy.
[d] Research Assistant, Department of Computer Engineering, University of Catania, University of Catania, Catania, Italy.
Corresponding author: Dr Rosalia Leonardi, Department of Orthodontics, University of Catania, via S. Sofia n 78, Catania, Italy (e-mail: rleonard@unict.it)

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Table 1. Technical Approaches[a] Used to Automatically Identify Cephalometric Landmarks and Their Advantages and Disadvantages

Techniques	Advantages	Disadvantages
Image filtering plus knowledge-based landmark search	1. Easy to implement 2. Image filtering techniques are well studied and a large number are available 3. By encoding proper anatomical knowledge better accuracy is achievable	1. Can fail to capture morphological variability in the radiographs 2. Filtering results are highly dependent on image quality and intensity level 3. Sensitive to noise in the image 4. Not all landmarks lie on edge and, moreover, the edges or curves are often unclear
Model-based approach	1. Is invariant to scale, rotation, and translation (the structure can be located even if it is smaller or bigger than the given model) 2. Accommodates shape variability	1. Needs models that must be created by averaging the variations in shape of each anatomical structure in a given set of radiographs 2. Model deformation must be constrained and is not always precise 3. Cannot be applied to partially hidden regions 4. Sensitive to noise in the image
Soft-computing or learning approach	1. Accommodates shape variability 2. Tolerant to noise 3. Techniques are well studied 4. Large selection of software tools available	1. Results depend on the training set 2. Difficult to interpret some results 3. A number of network parameters, such as topology and number of neurons, must be determined empirically

[a] Hybrid approaches, which are a combination of the listed approaches are not reported.

cephalometric analysis are usually systematic or random errors[3,8,9]; the latter involves tracing, landmark identification and measurement errors. Computerized or computer-aided, cephalometric analysis eliminates the mechanical errors when drawing lines between landmarks as well as those made when measuring with a protractor.

However, the inconsistency in landmark identification is still an important source of random errors both in computer-aided digital cephalometry and in manual cephalometric analysis.[8–10] In fact, variability in landmark identification has been determined to be five times greater than measurement variability,[11,12] with both methods open to considerable subjectivity. Last, but not least, both methods are time-consuming, although to a different extent.

For these reasons there have been efforts to automate cephalometric analysis with the aim of reducing the time required to obtain an analysis, improving the accuracy of landmark identification and reducing the errors due to clinicians' subjectivity.[13] Most of these efforts are meant initially for research only, but very soon completely automatic methods will become increasingly available for clinical purposes in addition to the computer-assisted method already described.[14] Therefore, some knowledge on this topic is desirable.

In an automated cephalometric analysis a scanned or digital cephalometric radiograph is stored in the computer and loaded by the software. The software then automatically locates the landmarks and performs the measurements for cephalometric analysis.

The challenging problem in an automated cephalometric analysis is landmark detection, given that the calculations have already been automated with success. The first attempt at automated landmarking of cephalograms was made by Cohen in 1984,[15] followed by more studies on this topic. Automatic identification of landmarks has been undertaken in different ways that involve computer vision and artificial intelligence techniques. All in all, these approaches can be classified into four broad categories, based on the techniques, or combination of techniques that have been employed. These categories are: (1) image filtering plus knowledge-based landmark search[16–20]; (2) model-based approaches[13,20–24]; (3) soft-computing approaches[25–31]; and (4) hybrid approaches.[32–37] The relative advantages and disadvantages of the technical approaches used to automatically identify cephalometric landmarks are summarized in Table 1.

Different levels of success in landmarking detection have been reported according to the specific approach used. Table 2 shows the experimental results that are reported in each study for each class of technical approach. This gives a first appraisal of the relative effectiveness of an approach. Yet, it is still not quite adequate enough to compare the techniques based on the specific cephalometric points to be detected. This is also because of the different reporting methods used in the various studies.

Indeed, notwithstanding the importance of this topic in today's digital world, only a description of the advantages and disadvantages for each approach has been presented. On the other hand, an analytic comparison between results obtained with different methods has never been reported.

In order to provide a comprehensive and contem-

Table 2. To Appraise the Effectiveness of the Four Classes of Methods for Automated Landmark Location, the Results Obtained With Each Technique Are Summarized by Indicating, for Each Experimental Work, the Number of Detected Landmarks, Accuracy Achieved, and the Number of X-Rays Used

Work	No. of X-rays	No. of Landmarks and Accuracy	Techniques
Image filtering plus knowledge-based landmark search			
Parthasarathy et al[17]	5	9 landmarks 58% < 2 mm (18% < 1 mm) mean error: 2.06 mm	Resolution pyramid Knowledge-based line extraction
Tong et al[18]	5	17 landmarks 76% < 2 mm mean error: 1.33 mm	Resolution pyramid Edge enhancement Knowledge-based extraction
Forsyth et al[19]	10	19 landmarks 4 > 2 mm 3 > 1 mm, 12 < 1 mm	Gray level value difference Edge location Knowledge-based extraction
Ren et al[20]	10	24 landmarks < 1 mm 19 landmarks < 0.5 mm 5 landmarks not identified	Image enhancement using image layer
Model-based approaches			
Cardillo et al[21]	40	20 landmarks 75% < 2 mm mean error: not reported	Pattern matching
Rudolph et al[24]	14	15 landmarks 13% < 2 mm mean error: 3.07 mm	Spatial spectroscopy Statistical pattern recognition
Hutton et al[13]	63	16 landmarks 35% < 2 mm (13% < 1 mm) mean error: 4.08	Active shape models
Romaniuk et al[23]	40	1 landmark mean error: 1.2 mm	Active contours with similarity function
Saad et al[22]	27	18 landmarks mean error > 2 mm	Active appearance model
Soft-computing approaches			
Innes et al[27]	109	3 landmarks 72% < 2 mm mean error: not reported	PCNN (pulse coupled neural networks)
Chakrabartty et al[31]	40	8 landmarks 93% < 1 mm	Support vector machines
Ciesielski et al[26]	36	4 landmarks 85% < 2 mm	Genetic algorithms
El-Feghi et al[29]	600	20 landmarks 90% < 2 mm mean error: not reported	Fuzzy neural networks
Hybrid approaches			
Liu et al[32]	38	13 landmarks 23% < 2 mm (8% < 1 mm) mean error: 2.86 mm	Edge detection Model fitting Knowledge-based algorithms
Grau et al[33]	20	17 landmarks 88.6% < 2 mm mean error: 1.03 mm	Edge detection Pattern matching
Yang et al[34]	11	16 landmarks 80% < 2 mm	Filtering Knowledge-based edge tracing Changeable templates
Giordano et al[37]	26	8 landmarks 85% < 2 mm (73% < 1 mm) mean error: 1.07	Cellular neural networks Knowledge-based extraction
Yue et al[35]	86	12 landmarks 71% < 2 mm	Filtering Edge tracking Pattern matching Active shape models

Table 3. Inclusion and Exclusion Criteria to Select Articles for Comparison

Inclusion Criteria	Exclusion Criteria
• Report of mean error between real position and estimated position of landmark for each point • Data in millimetre • Articles in English • Articles published from January 1966 to August 2006	• Review articles, abstracts, and letters • Data in pixel • Total mean error of the method for a large set of landmarks • Descriptive methods • Computerized-assisted method • Only graphic data on accuracy of landmark location • Recognition rate presented as percentage of success • Automatic measurements not landmarks • Cephalometric points not stated • Not every landmark detected is a cephalometric point

porary overview, this literature review was undertaken with the aim of describing the techniques used to highlight the strengths and weaknesses of each, and to review the percentage of success in locating each cephalometric point in order to establish a baseline for future searches.

MATERIALS AND METHODS

Searching Strategies

The strategy for this review was influenced mainly by the National Health Service Center for Reviews, Dissemination and by the Institute of Electrical and Electronics Engineers Inc, and by ISI Web of Science (WoS) Citation Index Expanded.

To identify all studies that examined automation of cephalographic landmarking, a literature survey was carried out searching in the following electronic databases: PubMed, (www.ncbi.nim.nih.gov), IEEE Explore (http://ieeexplore.ieee.org/Xplore/guesthome.jsp), and ISI WoS Science Citation Index Expanded (http://portal.isiknowledge.com). The survey covered the period from January 1966 to July 2006 for PubMed and IEEE, and January 1986 to July 2006 for ISI. In order to develop search terms for databases, the MeSH (Medical Subject Heading) database was used to look for MeSH terms for "cephalometry." According to this search the following term "cephalomet*, was crossed with a combination of the following terms: "computer, automat*, orthod*, skull, landmark*."

Selection Criteria

The following inclusion criteria were chosen to initially select potential articles from the published abstract results: identification of cephalometric landmarks; automatic or automatically; image processing; article in English; and no reviews and opinion articles. No attempts were made at this stage to identify which studies did not adequately report the accuracy of each computerized automatic method. It was considered improbable that the abstracts would provide enough information regarding validity, and this would potentially exclude some articles. No restrictions were set for sample size.

Eligibility of the selected studies was determined by reading the abstracts of the articles identified by each database. All articles that appeared to meet the inclusion criteria were selected and collected. The selection process was made by two researchers independently, and then the results were compared. If discrepancies were found, the three researchers made a final decision together (observer agreement for this selection: k $= 0.87 \pm 0.02$). Articles in which the abstract did not present enough relevant information to be included were also reviewed before making a final decision.

All article abstracts that appeared to meet the initial inclusion criteria were selected, and the actual articles were then downloaded. The reference lists of the retrieved articles were also checked for additional studies. The selection process was independently conducted by two researchers and their results compared. Any discrepancies were settled through discussion. The articles ultimately selected were chosen with the additional inclusion and exclusion criteria presented in Table 3.

RESULTS

The search strategy resulted in 118 articles. After selection according to inclusion and exclusion criteria, eight articles qualified for the final analysis (Table 4). Some articles (3 studies) were retrieved from more than one electronic database (Medline and ISI). Comparing the results between databases, Medline included the most studies (five articles). In the case of IEEE two articles were included and five were selected from ISI. Any article was retrieved by hand searching.

Interestingly, three articles out of eight used hybrid approaches, three papers model-based approaches, and two studies the image filtering plus knowledge-based landmark search. No article of the soft-computing approaches qualified for the final analysis.

Many articles were rejected for different reasons. Among these the most frequent was that results of accuracy for automatic landmark recognition were pre-

Table 4. Mean and Standard Deviation (When Reported) for Each Point Automatically Detected

	Parthasarathy et al[17]	Tong et al[18]	Rudolph et al[24]	Liu et al[32]	Hutton et al[13]	Grau et al[33]	Giordano et al[37]	Saad et al[22]
Nasion	1.828		2.57 ± 2.18	2.32 ± 0.54	5.6 ± 2.4	1.4	1.12 ± 1.11	2.965 ± 1.846
Sella	1.406		5.06 ± 3.37	0.94 ± 0.54	5.5 ± 6.8	1.92		3.24 ± 2.852
Orbitale		1.28	2.46 ± 3.77	5.28 ± 4.10	5.5 ± 3.4	1.92		3.422 ± 2.428
Porion		5.13	5.67 ± 3.37	2.43 ± 2.10	7.3 ± 6.5			3.480 ± 2.459
Gonion	1	2.72		4.53 ± 3.13	5.8 ± 6.0	1.11		3.636 ± 1.763
Menton			3.09 ± 3.46	1.90 ± 0.57	2.7 ± 3.6	0.48	0.62 ± 0.82	4.408 ± 2.031
Gnation				1.74 ± 0.86	2.7 ± 3.4	1.44		4.215 ± 1.778
Pogonion	2.91		1.85 ± 2.26	2.53 ± 1.12	2.7 ± 3.4	0.95	0.87 ± 1.34	3.657 ± 1.742
Point B	3.29		1.85 ± 2.09	3.69 ± 1.55	2.6 ± 2.7		2 ± 3.3	2.226 ± 1.237
Posterior nasal spine	2.16				5.0 ± 4.1	1.32		3.038 ± 1.377
Anterior nasal spine	2.36		2.64 ± 3.06	2.90 ± 1.12	3.8 ± 2.2	0.75		2.701 ± 1.050
Point A		0.78	2.33 ± 2.63	4.29 ± 1.56	3.3 ± 2.4	0.9	1.34 ± 0.82	2.545 ± 0.965
Upper incisor root	1.53	1.71	2.17 ± 2.98		2.9 ± 2.6	0.54		2.093 ± 1.001
Upper incisor tip	2.09	1.15	2.02 ± 1.99	2.36 ± 2.01	2.9 ± 3.8	0.9	0.48 ± 0.6	3.653 ± 1.593
Lower incisor root			2.67 ± 3.02		3.9 ± 2.7	0.89		3.522 ± 2.115
Lower incisor tip			2.46 ± 2.49	2.86 ± 1.24	3.1 ± 2.3	0.84	0.92 ± 0.94	3.147 ± 2.301
Occlusal plane 1								2.175 ± 1.105
Occlusal plane 2								2.038 ± 1.361
Lip superior		0.54						
Lip inferior		0.34						

sented as a percentage of success. Although the standard deviation of mean error is needed for a correct interpretation of the clinical significance of the findings, not reporting it was not considered as a reason to reject. Only one study reported enough automatically detected points to perform a cephalometric analysis.[21]

Basion point was not studied in any investigation, and the occlusal plane was used in only one investigation. Except for one study the mean errors of automatically detected points were over 2 mm, and standard deviations, when reported, also showed high values.

DISCUSSION

Advances and affordability in digital radiographic imaging have recently increased the demand for the medical profession to automate analysis and diagnostic tasks that were once performed manually. In this respect, several attempts to automate cephalometric analysis have been carried out.

However, data in the literature is sparse. Accordingly, this literature review was undertaken to identify, select, critically appraise, and summarize relevant research in order to establish a baseline for future search.

From this literature review many studies seemed to be methodologically unsound. This concern regards the inclusion criteria of patient radiographs, the number of radiographs used, the error level to create a comparison with and the absence of any standard deviation of the mean error.

A marked difference in results between included studies was found. It consisted in heterogeneity in the performance of techniques to detect the same landmark. Hybrid approaches detected sella point with a higher accuracy, contrary to the results for the same point obtained by the model-based approach. This can be due to the high variability of the shape of sella. Porion, gonion and anterior nasal spine were also identified with a higher precision by the hybrid approach. On the other hand, the capability to detect nasion was nearly the same in the knowledge based, model based and hybrid techniques. All in all, the approach that yields better results, with accuracy close to the one suitable for clinical practice, is the one which uses hybrid techniques.

Surprisingly, what emerges from this systematic review is that most of the studies reported amazing values for standard errors and standard deviations that are far from standard errors for landmark identification.

In orthodontic practice and research, it has been recommended that 0.59 mm of total error for the x coordinate and 0.56 mm for the y coordinate are acceptable levels of accuracy.[38] Therefore, the Euclidian value of error should be ±0.81 mm.

Unfortunately, none of the studies published on automatic landmark location refer to this latter value, and often a ≤2 mm difference between the location of landmark, obtained by some automatic method and that obtained by the human operator, has been considered by most people to be successful and a ≤4 mm distance acceptable.[29,35,39] Therefore, all the conclusions drawn from the studies are much more optimistic than reality and allow readers to think incorrectly that automatic cephalometric analysis will be available in the very near future. Moreover, if one considers that two cephalometric points are needed to trace a reference plane or line, the resulting special position of the line will be affected by the errors of two points, not a single one, and thus the error will be increased.

Moreover, in the few studies presenting an agreement between manual and computer-assisted methods in millimeters, most consider the Euclidian value, and do not refer to the x-axis and y-axis. This way of evaluating the validity of a computerized technique to locate landmarks is not the gold standard, as landmark identification is always associated with an error, which follows a certain pattern envelope. The identification of A or B point, for example, is prone to error in the perpendicular rather than in the horizontal plane.[5,40]

The use of these techniques for clinical purposes to provide initial landmark estimates could be a great help. In fact, automatic systems with the possibility for the orthodontist to correct or modify the position of landmarks found by the computerized landmarking approach could provide a future advantage in time saved and increased accuracy of the cephalometric analysis.

Actually, the ability to automatically identify landmarks is fair for many landmarks, but for routine clinical use it must be reliable. It should be emphasized that if automatic landmarking shall be used, it has to be with respect to validity, reliability, and costs. Unfortunately, in most instances the errors in landmark detection were greater in every automated system than those expected with manual tracing.[3,38,40] With the advance of digital radiography, this latter limit could be overcome and automatic detection of landmarks will become better established.

CONCLUSIONS

- Automatic landmarking is the first and last step in the development of a completely automatic cephalometric analysis.
- Four broad categories, based on the techniques or combination of techniques have been employed. These categories are: image filtering plus knowledge-based landmark search, model-based approaches, soft-computing approaches, and hybrid approaches.
- The systems described in the literature are not accurate enough to allow their use for clinical purposes as errors in landmark detection were greater than those expected with manual tracing.

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