RESEARCH ARTICLE

A preliminary study for determination of three-dimensional root apex position of the maxillary teeth using camera calibration technology

¹Hyun Jun Oh, ²Il-Hyung Yang and ²Seung-Hak Baek

¹Former Student, School of Dentistry, Seoul National University and Private Practice, Seoul, Republic of Korea; ²Department of Orthodontics, School of Dentistry, Dental Research Institute, Seoul National University, Seoul, Republic of Korea

Objectives: To propose a novel method for determining the three-dimensional (3D) root apex position of maxillary teeth using a two-dimensional (2D) panoramic radiograph image and a 3D virtual maxillary cast model.

Methods: The subjects were 10 adult orthodontic patients treated with non-extraction. The multiple camera matrices were used to define transformative relationships between tooth images of the 2D panoramic radiographs and the 3D virtual maxillary cast models. After construction of the root apex-specific projective (RASP) models, overdetermined equations were used to calculate the 3D root apex position with a direct linear transformation algorithm and the known 2D co-ordinates of the root apex in the panoramic radiograph. For verification of the estimated 3D root apex position, the RASP and 3D-CT models were superimposed using a best-fit method. Then, the values of estimation error (EE; mean, standard deviation, minimum error and maximum error) between the two models were calculated.

Results: The intraclass correlation coefficient values exhibited good reliability for the landmark identification. The mean EE of all root apices of maxillary teeth was 1.88 mm. The EE values, in descending order, were as follows: canine, 2.30 mm; first premolar, 1.93 mm; second premolar, 1.91 mm; first molar, 1.83 mm; second molar, 1.82 mm; lateral incisor, 1.80 mm; and central incisor, 1.53 mm.

Conclusions: Camera calibration technology allows reliable determination of the 3D root apex position of maxillary teeth without the need for 3D-CT scan or tooth templates.

Dentomaxillofacial Radiology (2016) **45**, 20150186. doi: [10.1259/dmfr.20150186](https://doi.org/10.1259/dmfr.20150186)

Cite this article as: Oh HJ, Yang I-H, Baek S-H. A preliminary study for determination of three-dimensional root apex position of the maxillary teeth using camera calibration technology. *Dentomaxillofac Radiol* 2016; **45**: 20150186.

Keywords: three-dimensional; calibration; panoramic radiograph; root apex position; virtual dental models

Introduction

Orthodontists have traditionally used panoramic radiographs to evaluate tooth angulation and root parallelism. However, two-dimensional (2D) information obtained from panoramic radiographs has several disadvantages. First, it provides distorted images of the dentition, resulting in some limitations for assessing tooth

angulation and root parallelism.^{1–6} Second, the root angulation images of the 2D panoramic radiograph are potentially different from those of three-dimensional (3D) CBCT.^{7,8} Therefore, it is necessary to determine the 3D position of the root apex using CT or CBCT images for the evaluation of tooth angulation and root parallelism. However, it is practically impossible to obtain CT or CBCT images for every evaluation owing to large scanning costs and high levels of radiation exposure.

To estimate the 3D root apex position without the help of 3D-CT scans, Pei et al⁹ proposed the use of 3D teeth templates for integration of 2D radiograph images and 3D dental models and reported that the mean distance error in the root regions was <2 mm. However, this method has the drawback of needing to construct 3D teeth templates. Recently, Lee et al¹⁰ demonstrated an *ex vivo* typodont model to define the 3D positions of the tooth crown and root using an initial CBCT scan and consecutive intraoral scans. After superimposition of the initial CBCT tooth model and the post-treatment intraoral scanned tooth model, the mean differences between the expected and true root positions of the maxillary and mandibular teeth were <2 mm.¹⁰ However, this method still has some problems, such as a need for the CBCT images and the assumption of no root resorption during orthodontic treatment.

In the field of computer vision and image processing, camera calibration technology has been used to map a 3D object using a 2D image.^{11–13} Using this concept, the 3D position of the root apex can be matched to the root apex in the 2D panoramic radiograph. Therefore, the purpose of this study was to propose a novel method for determining the 3D root apex position of maxillary teeth using a 2D panoramic radiograph image and a 3D virtual maxillary cast model.

Methods and materials

Demographic characteristics of the subjects

The subjects were 10 adult orthodontic patients (3 males and 7 females; average age, 22 years 6 months $\pm$ 4 years 5 months) who were treated with non-extraction approach and orthognathic surgery. Impressions for study models, panoramic radiographs (OP100; Instrumentarium Imaging Co., Tuusula, Finland) and 3D-CT models (Somatom[®] Sensation 10; Siemens, Erlangen, Germany) were taken on the same day or no longer than 2 days apart. The CT exposure conditions were as follows: 120 kVp and 80 mAs with a slice thickness of 0.75 mm, a pixel size of 0.75 mm, reconstruction kernel of H60s sharp mode and 1.0 pitch using the CT software (syngo[®] 2006G; Siemens, Erlangen, Germany). After the impressions were taken, the 3D virtual maxillary cast model was fabricated with a 3D laser scanner (Orapix, Seoul, Korea; accuracy level: ± 0.02 mm/100 mm scanning length; resolution: 1024 $\times$ 768 pixels) and 3Txxr 2.5 program

(Orapix). This study was reviewed and approved by the Institutional Review Board of Seoul National University Dental Hospital (IRB number, CRI13002).

Transformation from the 3D object of the root to the 2D image of the root for each tooth

The camera matrix has been used to define the transformation from a 3D object to a 2D image.^{11–13} However, because the X-ray source regarded as a camera centre was rotated and the film moved while the panoramic radiograph was being taken, a conventional camera matrix could not be applied to this study. Therefore, multiple camera matrices were used to describe the multiple root objects and the root apex-specific camera models were constructed, defining the region of interest as the area of each root for each camera projection (Figure 1). The equation of multiple camera matrices between the 3D object of the root and the 2D image of the root for each tooth was defined as follows:

$$x = P_i X \quad (1)$$

where P_i is the camera matrix defined for each root; $i = 1, \dots, R$ (the total root number for each tooth); x is the 2D co-ordinates of the known root apex in the panoramic radiograph; and X is the 3D co-ordinates of the root apex to be estimated.

After the landmarks were established on the palatal surface of teeth in the 3D virtual maxillary cast model (Figure 2), corresponding landmarks in the 2D panoramic radiograph were established using the same method with the landmarks in the 3D virtual maxillary cast model (Figure 3). The number of corresponding landmark pairs for each tooth was heuristically determined with trial and error (Table 1). Given a set of points in the 3D co-ordinates and a set of corresponding landmarks in the 2D image, the camera matrix was computed based on the 3D to 2D projective mapping.^{14,15}

Estimation of the root apex in the three-dimensional co-ordinates

The multiple camera matrices were computed from the corresponding landmarks using overdetermined equations with a direct linear transformation algorithm.^{13,16–18} The 3D co-ordinates of the root apex were estimated by the back-projection of the 2D

Figure 1 Examples of the region of interest in the right maxillary central incisor and second premolar in the three-dimensional virtual maxillary cast model and two-dimensional panoramic radiograph.

Figure 2 Definitions of the landmarks on the palatal surface of the clinical crown of the three-dimensional (3D) virtual maxillary cast model. L₁, the palatal axis point corresponding with the facial axis point on the labial or buccal surface; L₂, the gingival point; L₃, L₄ and L₅; the occlusal-most, left-most and right-most points of the palatal axis, respectively; L₆, the midpoint of L₁ and L₂; L₇, the midpoint of L₁ and L₃; L₈, the midpoint of L₁ and L₄; L₉, the midpoint of L₁ and L₅; L₁₀, the intersection point between the line passing L₈ parallel with the L₂–L₃ line and the another line passing L₆ parallel with the L₄–L₅ line; L₁₁, the intersection point between the line passing L₉ parallel with the L₂–L₃ line and the another line passing L₆ parallel with the L₄–L₅ line; L₁₂, the midpoint of L₂ and L₆; L₁₃, the midpoint of L₂ and L₁₂. Subsequent landmarks were defined in the same way. Landmarks in the two-dimensional panoramic radiograph were defined consistently with those in the 3D virtual cast model.

co-ordinates of the root apex in the panoramic radiograph using the computed camera matrices as follows:

$$X(\lambda_i) = P^+ x + \lambda_i C \quad (2)$$

where $X(\lambda_i)$ is the 3D co-ordinates of the apex of each root i ; P^+ is the pseudoinverse of P , given by

$P^+ = P^T (PP^T)^{-1}$, in which $P = [M|p_4]$; M is a 3×3 matrix; p_4 is a 3×1 matrix; and C is the camera centre determined by $C = -M^{-1}p_4$.

When the distance between an object and the camera centre is greater than the depth variation of the object, the affine camera model can be used.^{11–13} In our conditions, along the line of sight, the depth variation

Figure 3 Estimation of the three-dimensional (3D) co-ordinates of the root apex (circles) in the 3D virtual cast model using the known two-dimensional (2D) co-ordinates of the root apex in the panoramic radiograph. After the landmarks both in the 3D virtual maxillary cast model and 2D panoramic radiograph are established, camera matrix can be computed and the root apex can be estimated using the camera matrix.

Table 1 Number of landmarks used in this study

Maxillary tooth on the right side	Number of landmarks
Central incisor	11
Lateral incisor	14
Canine	20
First premolar (one common root or palatal root ^a)	18
Second premolar (one common root or palatal root ^a)	10
First molar (palatal root)	13
Second molar (palatal root)	17

^aIf the premolar had one common root, that common root was tested. If the roots of the premolar bifurcated, the palatal root was tested.

among the landmarks was relatively small compared with the distances between the landmarks on the crown and the root apex. Therefore, the transformation from the 3D co-ordinates in the 3D virtual maxillary cast model to the 2D co-ordinates in the panoramic radiograph was regarded as the projection by the affine camera. Therefore, using the approximated ratios of the lengths among line pairs, consisting of the landmarks and general camera properties of preservation of incidence and collinearity (Figure 4), the values of the unknown parameter λ_i can be calculated as follows:

$$|X(\lambda_{ij}) - L_\alpha| : |L_\beta - L_\gamma| \approx |l_x - l_\alpha| : |l_\beta - l_\gamma| \quad (3)$$

where $X(\lambda_{ij})$ is the 3D co-ordinate of the estimated root apex determined by the j^{th} equation of $X(\lambda_i)$; L_α , L_β and L_γ are the 3D co-ordinates of the known landmarks in the 3D virtual maxillary cast model; l_x is the 2D co-ordinates of the known root apex in the panoramic radiograph; and l_α , l_β and l_γ are the 2D co-ordinates of the known landmarks in the panoramic radiograph.

For each root i , the values of λ_{ij} are similar but not the same. Therefore, the value of 3D root apex co-ordinates, $X(\lambda_i)$ is estimated as the mean value in this study as follows:

$$X(\lambda_i) \approx \frac{1}{N} \sum_{j=1}^N X(\lambda_{ij}) \quad (4)$$

where $j = 1, \dots, N$, and N is the number of the equations.

Verification by CT scan data

The digital imaging and communications in medicine data obtained from the CT scan were exported into the 3Txxr 2.5 program (Orapix) to construct 3D-CT models of whole maxillary teeth, including roots (Figure 5).

Since the root information was not incorporated into the 3D virtual maxillary cast model, the 3D information of the roots in the 3D-CT model could be regarded as the true value. For verification of the estimated 3D root apex position, the 3D virtual maxillary cast model and the 3D-CT model were superimposed with a best-fit method^{19,20} using the whole crowns as the reference area (Figure 5). The 3D co-ordinates of the roots apex were measured with Rapidform 2006 (INUS Technology, Inc., Seoul, Korea). The values of estimation error (EE; mean,

standard deviations, minimum errors and maximum errors) were calculated based on the Euclidean distances between the estimated 3D root apex of the 3D virtual maxillary cast model and the true values from the 3D-CT model.

After 5 patients were randomly selected among 10 patients, the landmarks on the 2D panoramic radiographs and the 3D virtual maxillary cast models were digitized with a 7-month interval by 1 examiner (HJO). The intraclass correlation coefficients (ICCs) for landmark identification were computed in order to assess intra-examiner reliability. Since the ICC values exhibited good reliability for landmark identification, the first set of measurements was used. In the 2D panoramic radiographs and the 3D virtual cast models, the ICC values range from 0.962 to 1.000 and from 0.942 to 1.000, respectively.

Results

The mean EE of all root apices was 1.88 mm (Table 2). The EE values for all teeth, in descending order, were as follows: canine, 2.30 mm; first premolar, 1.93 mm; second premolar, 1.91 mm; first molar, 1.83 mm; second molar, 1.82 mm; lateral incisor, 1.80 mm; and central incisor, 1.53 mm (Table 2).

Discussion

In this study, there were two assumptions: first, transformative relationships between the image of each tooth in the 2D panoramic radiograph and the 3D virtual maxillary cast model can be defined,^{11–13,16–18} second, the 3D to 2D transformation can be approximated to the projection by the affine camera.^{11–13}

Determination of the 3D root apex position in the present study was based on the back-projection of the

Figure 4 Schematic relationship of the line pairs consisting of the known landmarks, the known two-dimensional 2D root apex and the unknown three-dimensional 3D root apex. $X(\lambda_{ij})$ is the 3D coordinate of the estimated root apex determined by the j^{th} equation of $X(\lambda_i)$. L_2 , L_3 , L_4 and L_5 are the 3D coordinates of the known landmarks in the 3D virtual maxillary cast model. l_x is the 2D coordinates of the known root apex in the panoramic radiograph. l_2 , l_3 , l_4 , and l_5 are the 2D coordinates of the known landmarks in the panoramic radiograph corresponding to L_2 , L_3 , L_4 and L_5 , respectively.

Figure 5 (a). The three-dimensional (3D) virtual maxillary cast model constructed with a 3D laser scanner and the 3Txxr program (Orapix, Seoul, Korea). (b). The 3D virtual dental model constructed using CT scan and segmented by the 3Txxr 2.5 program. (c). Superimposition of the 3D virtual maxillary cast model and the 3D-CT model using a best-fit method.

root apex of the 2D panoramic radiograph. If the 3D co-ordinates of the root apex are accurately determined, tooth angulation and root parallelism can be analysed.

Although the range of EE values was from 1.53 to 2.30 mm (Table 2), the estimation of the 3D root apex position of the maxillary teeth was possible without the help of 3D-CT scanning or tooth templates. When the values were compared with those of the previous studies relying on such aid (1.21 mm of Pei et al⁹ and 1.86 mm of Lee et al;¹⁰ Table 3), there was no significant difference in the values obtained from our study and previous studies. The method used in this study might be reliable because most of the EE values were <2 mm (Table 2). However, the EE values were relatively large at the maxillary canine (2.30 mm), first premolar (1.93 mm) and second premolar (1.91 mm) compared with the mean EE (1.88 mm) (Table 2). This disparity is likely due to the discrepancies between the optimal and actual beam directions of the panoramic radiograph in the maxillary canine and premolar areas.¹⁻³

In their study, using a 3D tooth template, Pei et al⁹ reported that the mean EE value of all roots was 1.21 mm (Table 3), which was less than that of the root apex in the present study (1.88 mm; Table 2). The mean EE values of each root in their study⁹ were also smaller than the results of our study (Table 3). However, since they did not measure the EE value of the root apex,⁹ there is a possibility that the EE value was underestimated by >1.21 mm. Two major disadvantages of the method by Pei et al⁹ include the need for 3D tooth template and high computational complexity. Our approach relied only on a 2D panoramic radiograph and a 3D virtual maxillary cast model, without the help of a 3D tooth template or CT images. In addition, Pei et al⁹ analysed overall 3D surface data, whereas we focused only on the root apex using predefined landmarks. Furthermore, since they used the iteration method for non-linear problems and the regression method for surface deformation,⁹ the computational complexity might be higher than that of our linear optimization method.

Table 2 Estimation errors

Maxillary tooth on the right side	Mean (mm)	Standard deviation (mm)	Minimum (mm)	Maximum (mm)
Central incisor	1.53	0.23	1.25	2.00
Lateral incisor	1.80	1.13	0.78	4.95
Canine	2.30	0.80	0.95	3.70
First premolar (common or palatal root ^a)	1.93	0.57	0.57	2.88
Second premolar (common or palatal root ^a)	1.91	0.82	0.53	3.21
First molar (palatal root)	1.83	0.50	0.64	2.73
Second molar (palatal root)	1.82	0.51	1.30	2.81
Total mean	1.88	0.65	0.86	3.18

^aIf the premolar had one common root, that common root was tested. If the roots of the premolar bifurcated, the palatal root was tested.

Table 3 Comparison of the estimation error values with those in previous studies

Mean estimation errors	Pei <i>et al</i> ⁹		Lee <i>et al</i> ¹⁰		This study	
	Maxillary teeth ^a	Mandibular teeth	Maxillary teeth	Mandibular teeth	Maxillary teeth	Mandibular teeth
Central incisor	1.05	NA	NA	NA	1.53	NA
Lateral incisor	1.24	NA	NA	NA	1.80	NA
Canine	1.18	NA	NA	NA	2.30	NA
First premolar	1.08	NA	NA	NA	1.93	NA
Second premolar	1.08	NA	NA	NA	1.91	NA
First molar	1.28	NA	NA	NA	1.83	NA
Second molar	1.59	NA	NA	NA	1.82	NA
Total mean	1.21	NA	1.86 ^b	0.83 ^b	1.88	NA

NA, not applicable.

^aMean value of the overall root region, not the value of the root apex itself.

^bMaximum value of the root region, not the value of the root apex itself (error of each tooth was not shown in the study).

Lee *et al*¹⁰ demonstrated that maximum discrepancy, which can be regarded as the EE of the root apex, was about 1.86 mm (Table 3). However, the mean discrepancy in their study included the whole crown and root regions. There are two main differences between the study by Lee *et al*¹⁰ and the present study. First, since Lee *et al*¹⁰ used the initial CBCT, it could be applicable to the cases of root resorption during orthodontic treatment. However, our method can analyse such cases since it was based on the concurrent panoramic radiographs reflecting the present shape of the root. Second, only one sample model was tested in the study by Lee *et al*¹⁰ which was not confirmed in clinical patients.

The results from this study might exhibit reliable estimation of the 3D root apex position of maxillary teeth without the need for 3D-CT scan or tooth templates. However, there are several factors to be considered in the experimental design and methodology. First, since the accuracy of the camera calibration parameters affects the results of subsequent tasks,^{21,22} determining the optimal number of corresponding landmarks is important for the estimation performance. Second this study relied on laborious manual digitization of the landmarks, whereas the automatic landmark detection

would produce a more efficient study.^{23–25} Third, since this study concentrated on the estimation of the root apex, 3D reconstruction of the whole root shape was not possible in this study. Fourth, further studies should include more subjects and multiple measurements for interclass agreement and statistical analysis, and to improve the methodology further studies are needed in order to get the errors down and to perform additional experiments for determining the quantitative level of clinical acceptance. Finally, in 3D reconstruction from two orthogonal images,^{26,27} 3D estimation of the root apex can be defined by image integration of the posteroanterior and lateral cephalograms. In addition, future studies should include subjects treated with extraction and should estimate the apices of buccal roots of the bifurcate maxillary premolars and the mesiobuccal and distobuccal roots of the maxillary molars.

Conclusions

Camera calibration technology allows reliable determination of the 3D root apex position of maxillary teeth without the need for 3D-CT scan or tooth templates.

References

- Philipp RG, Hurst RV. The cant of the occlusal plane and distortion in the panoramic radiograph. *Angle Orthod* 1978; **48**: 317–23. doi: [10.1043/0003-3219\(1978\)048<0317:TCOTOP>2.0.CO;2](https://doi.org/10.1043/0003-3219(1978)048<0317:TCOTOP>2.0.CO;2)
- Samawi SSB, Burke PH. Angular distortion in the orthopantomogram. *Br J Orthod* 1984; **11**: 100–7. doi: [10.1179/bjo.11.2.100](https://doi.org/10.1179/bjo.11.2.100)
- Scarfe WC, Nummikoski P, McDavid WD, Welander U, Tronje G. Radiographic interproximal angulations: implications for rotational panoramic radiography. *Oral Surg Oral Med Oral Pathol* 1993; **76**: 664–72. doi: [10.1016/0030-4220\(93\)90079-J](https://doi.org/10.1016/0030-4220(93)90079-J)
- Wyatt DL, Farman AG, Orbell GM, Silveira AM, Scarfe WC. Accuracy of dimensional and angular measurements from panoramic and lateral oblique radiographs. *Dentomaxillofac Radiol* 1995; **24**: 225–31. doi: [10.1259/dmfr.24.4.9161166](https://doi.org/10.1259/dmfr.24.4.9161166)
- Farman AG. *Panoramic radiology*. Berlin Heidelberg, Germany: Springer-Verlag; 2007. pp. 84–9.
- Owens AM, Johal A. Near-end of treatment panoramic radiograph in the assessment of mesiodistal root angulation. *Angle Orthod* 2008; **78**: 475–81. doi: [10.2319/040107-161.1](https://doi.org/10.2319/040107-161.1)
- Peck JL, Sameshima GT, Miller A, Worth P, Hatcher DC. Mesiodistal root angulation using panoramic and cone beam CT. *Angle Orthod* 2007; **77**: 206–13. doi: [10.2319/0003-3219\(2007\)077\[0206:MRAUPA\]2.0.CO;2](https://doi.org/10.2319/0003-3219(2007)077[0206:MRAUPA]2.0.CO;2)
- Bouwens DG, Cevidanes L, Ludlow JB, Phillips C. Comparison of mesiodistal root angulation with posttreatment panoramic radiographs and cone-beam computed tomography. *Am J Orthod Dentofacial Orthop* 2011; **139**: 126–32. doi: [10.1016/j.ajodo.2010.05.016](https://doi.org/10.1016/j.ajodo.2010.05.016)
- Pei Y, Shi F, Chen H, Wei J, Zha H, Jiang R, et al. Personalized tooth shape estimation from radiograph and cast. *IEEE Trans Biomed Eng* 2012; **59**: 2400–11. doi: [10.1109/TBME.2011.2174993](https://doi.org/10.1109/TBME.2011.2174993)
- Lee RJ, Pham J, Choy M, Weissheimer A, Dougherty HL Jr, Sameshima GT, et al. Monitoring of typodont root movement via crown superimposition of single cone-beam computed tomography and consecutive intraoral scans. *Am J Orthod Dentofacial Orthop* 2014; **145**: 399–409. doi: [10.1016/j.ajodo.2013.12.011](https://doi.org/10.1016/j.ajodo.2013.12.011)
- Trucco E, Verri A. *Introductory techniques for 3-D computer vision*. Upper Saddle River, NJ: Prentice-Hall Inc.; 1998.
- Shapiro LG, Stockman GC. *Computer vision*. Upper Saddle River, NJ: Prentice-Hall Inc.; 2001.
- Hartley R, Zisserman A. *Multiple view geometry in computer vision*. New York, NY: Cambridge University Press; 2004.
- Tsai RY. A versatile camera calibration technique for high-accuracy 3D machine vision metrology using off the-shelf TV cameras and lenses. *IEEE J Robot Autom* 1987; **3**: 323–44. doi: [10.1109/JRA.1987.1087109](https://doi.org/10.1109/JRA.1987.1087109)

15. Sun W, Cooperstock JR. An empirical evaluation of factors influencing camera calibration accuracy using three publicly available techniques. *Mach Vis Appl* 2006; **17**: 51–67. doi: [10.1007/s00138-006-0014-6](https://doi.org/10.1007/s00138-006-0014-6)
16. Abdel-Aziz YI, Karara HM. Direct linear transformation from comparator coordinates in to object space coordinates in close range photogrammetry. *Proc Symp Close-Range Photogrammetry* 1971; 1–18.
17. Faugeras OD, Toscani G. Calibration problem for stereo. Proceedings of the International Conference on Computer Vision and Pattern Recognition. Miami, FL; 1986. p. 15–20.
18. Heikkilä J. Geometric camera calibration using circular control points. *IEEE Trans Pattern Anal Mach Intell* 2000; **22**: 1066–77. doi: [10.1109/34.879788](https://doi.org/10.1109/34.879788)
19. Lavalée S, Szeliski R, Brunie L. Matching 3-D smooth surfaces with their 2-D projections using 3-D distance maps. *Proc SPIE* 1991; **1570**: 322–36.
20. Commer P, Bourauel C, Maier K, Jäger A. Construction and testing of a computer-based intraoral laser scanner for determining tooth positions. *Med Eng Phys* 2000; **22**: 625–35. doi: [10.1016/S1350-4533\(00\)00076-X](https://doi.org/10.1016/S1350-4533(00)00076-X)
21. Weng J, Cohen P, Herniou M. Camera calibration with distortion models and accuracy evaluation. *IEEE Trans Pattern Anal Mach Intell* 1992; **14**: 965–80. doi: [10.1109/34.159901](https://doi.org/10.1109/34.159901)
22. Wu YH, Li YF, Hu ZY. Detecting and handling unreliable points for camera parameter estimation. *Int J Comput Vis* 2008; **79**: 209–23. doi: [10.1007/s11263-007-0114-4](https://doi.org/10.1007/s11263-007-0114-4)
23. Vucinić P, Trpovski Z, Šćepan I. Automatic landmarking of cephalograms using active appearance models. *Eur J Orthod* 2010; **32**: 233–41.
24. Zheng Y, John M, Liao R, Boese J, Kirschstein U, Georgescu B, et al. Automatic aorta segmentation and valve landmark detection in C-arm CT: application to aortic valve implantation. *Med Image Comput Comput Assist Interv* 2010; **13**: 476–83.
25. Shahidi Sh, Oshagh M, Gozin F, Salehi P, Danaei SM. Accuracy of computerized automatic identification of cephalometric landmarks by a designed software. *Dentomaxillofac Radiol* 2013; **42**: 20110187. doi: [10.1259/dmfr.20110187](https://doi.org/10.1259/dmfr.20110187)
26. Ning J, McClean S, Cranley K. Using simulated annealing for 3D reconstruction of orthopedic fracture. *Med Phys* 2004; **31**: 2184–91. doi: [10.1118/1.1760189](https://doi.org/10.1118/1.1760189)
27. Filippi S, Motyl B, Bandera C. Analysis of existing methods for 3D modelling of femurs starting from two orthogonal images and development of a script for a commercial software package. *Comput Methods Programs Biomed* 2008; **89**: 76–82. doi: [10.1016/j.cmpb.2007.10.011](https://doi.org/10.1016/j.cmpb.2007.10.011)