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Scientific Section

Random Errors in Localization of Landmarks in Postero-anterior Cephalograms

A. E. ATHANASIOU, D.D.S., M.S.D., DR.DENT.

Department of Orthodontics, School of Dentistry, Aristotle University of Thessaloniki, Thessaloniki, Greece.

R.-R. MIETHKE, D.D.S., M.D., DR.MED.DENT., PH.D.

Department of Orthodontics and Dentofacial Orthopedics, Centre of Dental Medicine, Charite University Clinic, Humboldt University, Berlin, Germany

A. J. W. VAN DER MEIJ, D.D.S.

Private Orthodontic Practice, The Hague, The Netherlands

Abstract: *The aim of the present study was to evaluate the random error in localization of the most common landmarks in postero-anterior cephalograms (PAC). The study took place at the Department of Orthodontics of Aarhus University during the period 1993–1995. The material consisted of 30 standardized PAC taken in natural head position. Five examiners had to identify 34 landmarks on each cephalogram. Subsequently, all examiners had to identify again the same 34 landmarks on one randomly selected cephalogram five times with a time interval of at least 24 hours. All landmarks were digitized, related to an X–Y co-ordinate system, and an arithmetical mean was calculated. The accuracy of digitizing was evaluated by digitizing one randomly selected cephalogram 10 times.*

The main findings of this study are: (1) The digitizing error is negligible compared to the errors introduced by landmark identification. (2) Each landmark has its own characteristic pattern of variance, which is very similar on both sides. (3) Significant differences in accuracy exist between the various postero-anterior landmarks. The six most accurate landmarks are mastoid left (l) and right (r), latero-orbitale (l) and (r), and antegonion (l) and (r). The six least accurate landmarks are coronoid (l) and (r), condylar (l) and (r), and mandibular foramen (l) and (r). (4) A significant difference in the accuracy of landmark identification between the five examiners was only seen for seven of the 34 landmarks. (5) No evidence was found that one examiner was consistently better/worse than the others. (6) No improvement in the accuracy was found after repeated identification, thus there seems to be no short-term 'learning process'.

Index words: Cephalometrics, Error of Identification, Landmark Identification, Posterior Anterior Cephalometrics.

Refereed Paper

Introduction

In patients with functional, dentoalveolar, and/or facial asymmetries, often detailed information in the transverse (and vertical plane) is needed which can be provided by postero-anterior cephalograms (PAC). PAC analyses allow quantitative (and qualitative) studies of the craniofacial skeleton. However, the impact of such analyses will greatly depend on their accuracy, which is basically the accuracy in identifying the relevant reference points. In a recent textbook on cephalometric radiography the technique, scope, different analyses, and sources of errors of postero-anterior cephalometry are comprehensively described (Athanasiou and Van der Meij, 1995).

Although several investigations have evaluated the random error in localization of landmarks on lateral cephalograms, only few studies exist about this aspect in PAC (El-Mangoury *et al.*, 1987; Major *et al.*, 1994, 1995). The study by El-Mangoury et al. (1987) used only one operator and did not report inter-examiner error. In the study of Major *et al.* (1994) the horizontal and vertical identification errors were determined for a sample of 33 skulls and 25 patients.

The aims of this study were (a) to evaluate the random localization error of the most common landmarks on PAC of patients, and (b) to assess the inter-observer and intra-observer accuracy in localizing these landmarks.

Materials and Methods

Materials

The material consisted of 30 PAC from the files of the Department of Orthodontics, University of Aarhus. Only PAC of excellent quality, from patients without orthodontic appliances, and severe craniofacial anomalies,

Correspondence: A. E. Athanasiou, Department of Orthodontics, School of Dentistry, Aristotle University of Thessaloniki, GR-54006 Thessaloniki, Greece (e-mail: aeathan@dent.auth.gr).

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taken in natural head position, with the same cephalostat with standardized equipment conditions were utilized.

Examiners

All cephalograms were evaluated by five postgraduate orthodontic students who were considered to have an equal level of knowledge, since all had participated in the same PAC course. In a pre-test, these examiners had to identify a series of PAC landmarks in order to judge their individual ability. All five examiners proved qualified to participate in this study. Postgraduate orthodontic students were chosen primarily on their availability, but also because of their interest and dedication to participate in this examination, and their presumed intellectual homogeneity. The possible effect of a different group of examiners on the results will be reflected in the discussion section of this article.

In the first part of this study the examiners had to identify 34 landmarks on all 30 PAC, using a list with their definitions exactly corresponding to the pertinent literature (Athanasiou and Van der Meij, 1995).

Initially, three registration points were marked directly on each PAC with a fine needle for identical superimposition of all tracings. Identical registration points were marked on tracing paper, which was placed on all cephalograms and secured with adhesive tape. All landmarks were marked with a 0·5-mm HB pencil under the same environment with no given time limit.

In the second part of this study all five examiners had to identify and number the same 34 landmarks on one, randomly selected PAC five times, with a time interval of at least 24 hours between repetitions.

Postero-anterior cephalometric landmarks

The 34 PAC landmarks evaluated in this study are presented in Fig. 1. Their definitions has been presented elsewhere (Athanasiou and Van der Meij, 1995).

Co-ordinate system

A co-ordinate system was constructed for every PAC with the true vertical, and the true horizontal as *Y*- and *X*-axis, respectively. The upper/lower edge of the cephalogram represented the true horizontal, the left/right edge the true vertical. Two of the three registration points were placed 18 cm apart parallel to the true horizontal. The third registration point was placed in the lower right corner of the PAC. By connecting the first two registration points and by constructing a perpendicular to the third point a fixed co-ordinate system for every cephalogram was obtained. The *X*/*Y* co-ordinate system was erected on all tracings after landmark identification was completed.

Digitizing. A calibrated digitizing table was used to register all landmarks. This digitizing table was also equipped with an *X*/*Y* co-ordinate system to which all tracings were matched. Again, to minimize the number of variables, all landmarks were digitized exclusively by one author (AJWVDM). Due to the co-ordinate system every recorded landmark could be described by an *X* and *Y* value.

To evaluate the digitizing error one randomly selected tracing was digitized by one of the authors (AJWVDM) 10 times, with 2-hour intervals, on different days, and under varying circumstances (e.g. just after starting the digitizer or after 3 hours of digitizing). The rationale for this attempt was to exclude that temperature changes could have influenced the accuracy of the equipment.

Scattergrams. Every landmark on every cephalogram was indicated by five points, corresponding to the localization by the five different examiners. To quantify the variation on the 30 different PAC, the arithmetical mean of the five *X* and *Y* values for every landmark was calculated. This arithmetical mean was the X_0/Y_0 co-ordinate of all scattergrams.

To evaluate the inter-examiner differences a Bonferroni *a posteriori* test was carried out. The level of significance was set at $P \leqslant 0{\cdot}05$.

Results

Digitizing error

The standard deviation of each landmark in *X* and *Y* direction is presented in Table 1. These standard deviations are very similar, not larger than 0·1 mm and negligible.

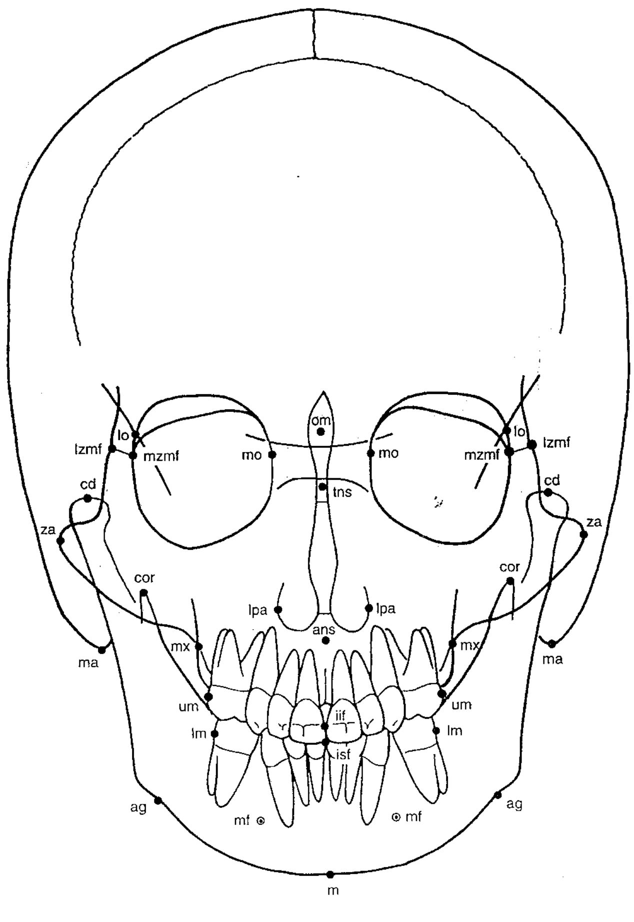

FIG. 1 PA cephalometric landmarks (abbreviated), which had to be localized in this study. Their definitions have been presented elsewhere (Athanasiou and Van der Meij, 1995).

TABLE 1 Standard deviation in X and Y direction (in mm) after digitizing one randomly chosen PAC 10 times

	Standard deviation	
Landmark	*X* co-ordinate	*Y* co-ordinate
ag (r)	0·06	0·05
ag (l)	0·06	0·04
ans	0·05	0·06
cd (r)	0·03	0·05
cd (l)	0·04	0·05
cor (r)	0·04	0·05
cor (l)	0·06	0·06
iif	0·04	0·04
isf	0·04	0·05
lpa (r)	0·05	0·05
lpa (l)	0·09	0·04
lo (r)	0·05	0·06
lo (l)	0·03	0·05
m	0·05	0·04
lm (r)	0·05	0·04
lm (l)	0·06	0·04
ma (r)	0·06	0·05
ma (l)	0·04	0·05
mx (r)	0·03	0·06
mx (l)	0·07	0·06
um (r)	0·03	0·05
um (l)	0·05	0·03
mo (r)	0·06	0·04
mo (l)	0·03	0·04
mf (r)	0·06	0·05
mf (l)	0·08	0·06
om	0·02	0·05
za (r)	0·04	0·07
za (l)	0·03	0·06
tns	0·03	0·06
mzmf (r)	0·03	0·04
mzmf (l)	0·04	0·05
lzmf (r)	0·03	0·1
lzmf (l)	0·04	0·07

Accuracy in landmark identification

Figures 2 and 3 present the deviation from the arithmetical mean for each landmark, in the *X* and *Y* direction, respectively. The ranges vary in the *X* direction from 2·0 mm for latero-orbitale (l) to 18·2 mm for mental foramen (r), and in the *Y* direction from 1·8 mm for mastoid (r) to 23·7 mm for coronoid (l).

The ranges in *X* and *Y* direction for the same landmark on the left and right side are obviously smaller than the ranges between different landmarks. An exception is the landmark mandibular molar, where the range in the *X* direction is 7·7 mm on the left and 13·9 mm on the right side.

Selected scattergrams in Figure 4 depict the ranges graphically. Each scattergram shows a characteristic distribution, its so-called envelope (Van der Meij, 1995).

The results can also be presented by calculating the percentage of localized landmarks within 0·5 mm/1·0 mm intervals separately for *X*- and *Y*- co-ordinates, since most envelopes have a non-circular shape (Table 2). Table 2 reveals further that, except for top of nasal septum and both coronoid processes, 50 per cent of the localized points lie within a distance of 2·0 mm in both *X* and *Y* direction, and that for 12 landmarks 90 per cent of the localized points are within this range. Furthermore, it becomes obvious that for mastoid (r) 99 per cent of the localized landmarks lie within a distance of 1·0 mm, whereas for coronoid (l) even 14 per cent of the localized landmarks lie 6·0 mm or more away from the arithmetical mean.

The 150 points of all scattergrams are not completely independent, but can be considered as 30 groups (30 PAC) of five landmarks (localized by the five examiners). Because of the lack of complete independence, the standard deviations were computed by the method of Baumrind and Frantz (1971) using the formula:

$$S = \sqrt{\Sigma d^2/N(K-1)}$$

where K is number of examiners (5), N is the number of PAC (30), d is the deviation of an individual point value from the arithmetical mean.

Since all 150 landmarks are characterized by an X and an Y co-ordinate, a vector $|v|$ can be calculated using the formula:

$$v = \sqrt{x^2 + y^2}$$

By summation of the 150 individual vectors $|v|$ an overall mean vector $|V|$ (Fig. 5) is calculated using the computation:

$$V = \frac{\Sigma\,|v|}{N}$$

where N is the number of vectors $|v|$ (150)

The magnitude of this vector expresses, independently of the direction, the accuracy that can be achieved in localizing a certain landmark. Because each localized landmark was numbered it could also be determined how close a respective examiner was in relation to the arithmetical mean (Fig. 6). Overall, it became obvious that almost all examiners had their deficiencies (Van der Meij, 1995).

Descriptive Statistics

Inter-examiner differences. Table 3 presents the standard deviation for each examiner and each landmark in *X* and *Y* direction, respectively. This table shows that the accuracy between examiners is greater than the accuracy between different landmarks.

A Bonferroni *a posteriori* test showed no significant difference between examiners for most landmarks. A significant difference (deviation from the arithmetical mean) could only be found for the landmarks incision inferior frontale, incision superior frontale (examiner 2), mandibular molar (r) and (l), maxillary molar (r) and (l) (examiner 4), and top nasal septum (examiner 3). Generally, there was no evidence that one examiner/some examiners was/were consistently localizing landmarks closer to/farther off the arithmetical mean than the others. The overall accuracy of each examiner was assessed by calculating the mean deviation in vector direction as explained previously (Table 4).

Intra-examiner differences. The general tendency and difficulty in localizing certain landmarks as found during the first part of this study was also seen during this repeated localization. Figure 7 shows the results for the landmarks zygomaticofrontal lateral suture point-out (r) (agreement within a range of less than 1·5 mm), as well as condylar (l) (agreement within a range of more than 5·0 mm).

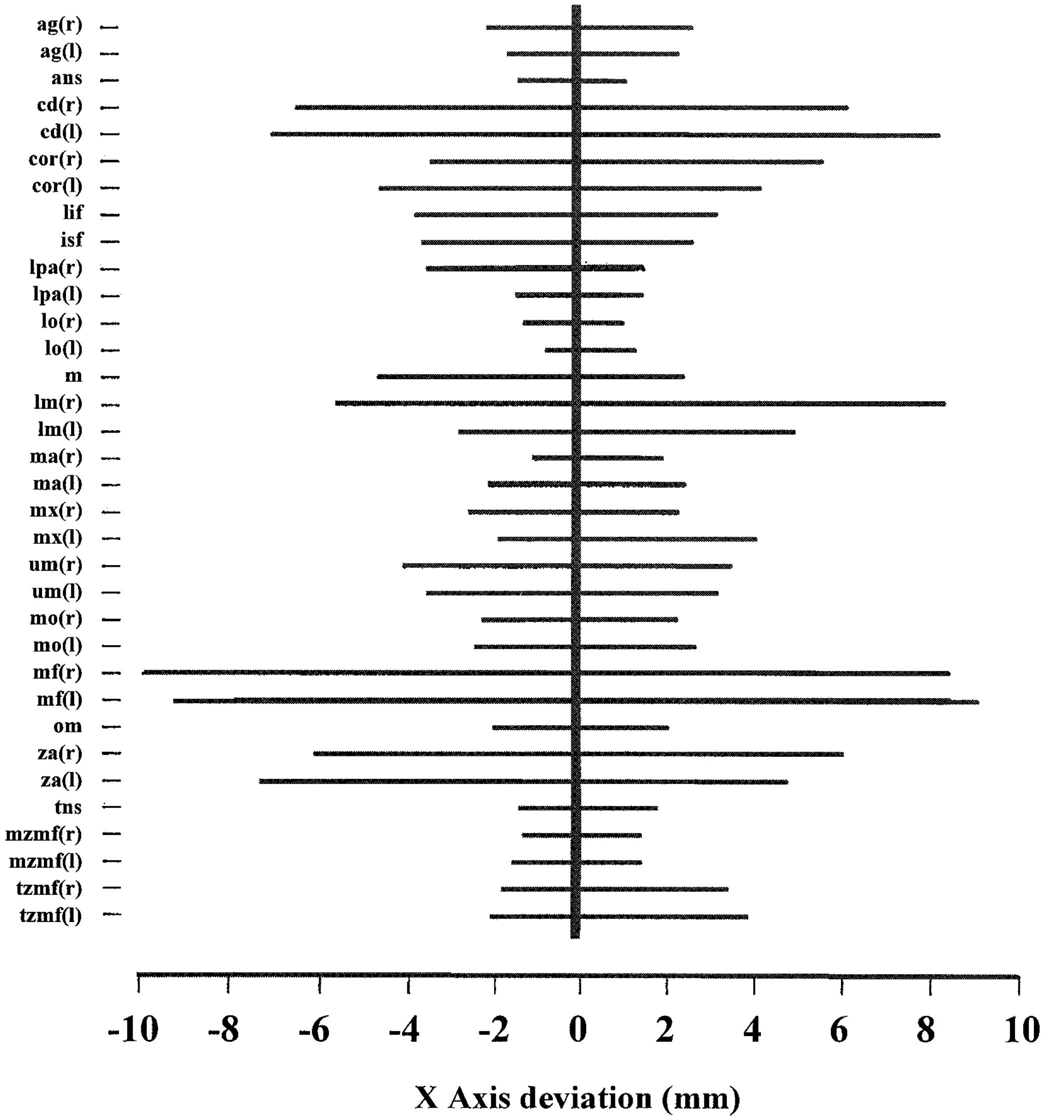

FIG. 2 Range of random localization error from the arithmetical mean for all landmarks, in *X* direction; r = right, l = left.

Discussion

PAC is used by researchers and clinicians for quantitative (and qualitative) evaluations of the craniofaciodental symmetry in the frontal plane. Apart from the quality of the cephalogram, and the accuracy of the digitizing equipment, the impact of such an evaluation mostly depends upon the accuracy with which an examiner can localize the relevant landmarks. This, again, depends on how precisely a certain landmark is defined and how experienced the examiner is, but most of all on the image characteristics of a given landmark. Therefore, this study focuses on the random localization error of the most common landmarks in PAC.

To limit the number of influencing variables—since the difficulty of landmark identification varies greatly between cephalograms—the material of this study consisted of 30 standardized cephalograms of excellent quality. It can be supposed that, with less qualitative cephalograms, the resulting localization errors would have been larger. However, it seems reasonable to also assume that neither the relatively accuracy nor the qualitative vectorial deviation would have been much different.

As mentioned previously, the experience of the examiner play a decisive role in the accuracy of landmark identification. Again, to limit the number of influencing variables, individuals with the same level of education and experience were appointed for this evaluation. Most likely, more experienced examiners would have localized certain landmarks with greater accuracy.

A general problem in assessing the identification accuracy of given landmarks is that their exact localization is unknown. Even a panel of the most acknowledged experts would possibly disagree upon the ideal localization, which means that there is no 'absolute truth'. To compensate this inherent shortcoming of the present study (and all similar ones), the arithmetical mean for every landmark was calculated by averaging the points identified by the five examiners in *X* and *Y* direction. This arithmetical mean

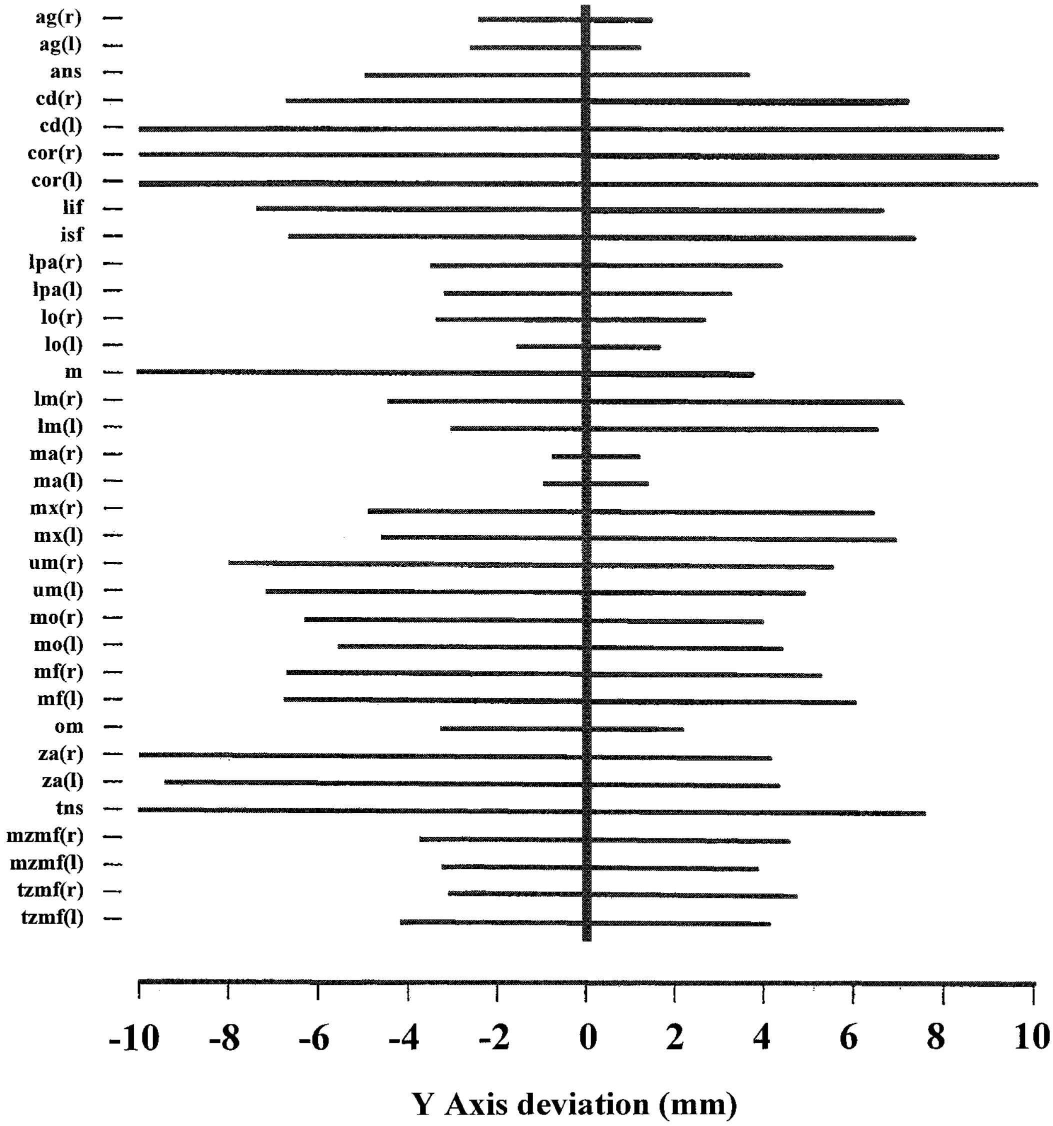

FIG. 3 Range of random localization error from the arithmetical mean for all landmarks, in Y direction; r = right, l = left.

(X_0/Y_0 co-ordinate) may not be the true location of a certain landmark, but for methodological purposes it can be regarded as closest to the 'absolute truth'. All scattergrams were created by superimposing all tracings on the X/Y co-ordinate system. These scattergrams then reveal the random error of localization for a certain landmark.

The construction of the co-ordinate systems, superimposition of tracings and the digitization of the landmarks were carried out by only one person to avoid additional errors. The digitizing error was assessed to be less than 0.1 mm. This error is negligible considering that the smallest deviation from the X_0/Y_0 co-ordinate is 1·8 mm.

Also, it should be stated that in this study only few outliners were found, but no extreme outliers, i.e. landmarks that were localized more than five standard deviations from the arithmetical mean.

The variation of localized landmarks around the arithmetical mean, as presented in Figures 2 and 3, is obviously very specific. In general, the range in X direction seems to be slightly smaller than that in Y direction (Van der Meij, 1995). A possible explanation for this could be that a landmark is easier to detect the more lateral its respective anatomical structure is located and, therefore, the lesser it will be influenced by the 'noise' of neighbouring entities.

Therefore, it is not surprising that the landmarks mastoid (r) and (l) exhibit a small, circular envelope: the mastoid process is not blurred by over-projection and, thus, its lowest point can easily be identified. Controversially, the identification of the dental landmarks maxillary molar (r) and (l), mandibular molar (r) and (l), incision inferior frontale and incision superior frontale is very difficult most probably due to over-projections of the total dentition, including unerupted teeth, crowding, amalgam restorations, and even bony structures such as the maxillary tuberosity. The same holds true for anterior nasal spine and top of the nasal septum. A range of 8·5 and 18·5 mm, respectively in Y direction, makes them almost useless as a reference point for evaluations in the vertical plane.

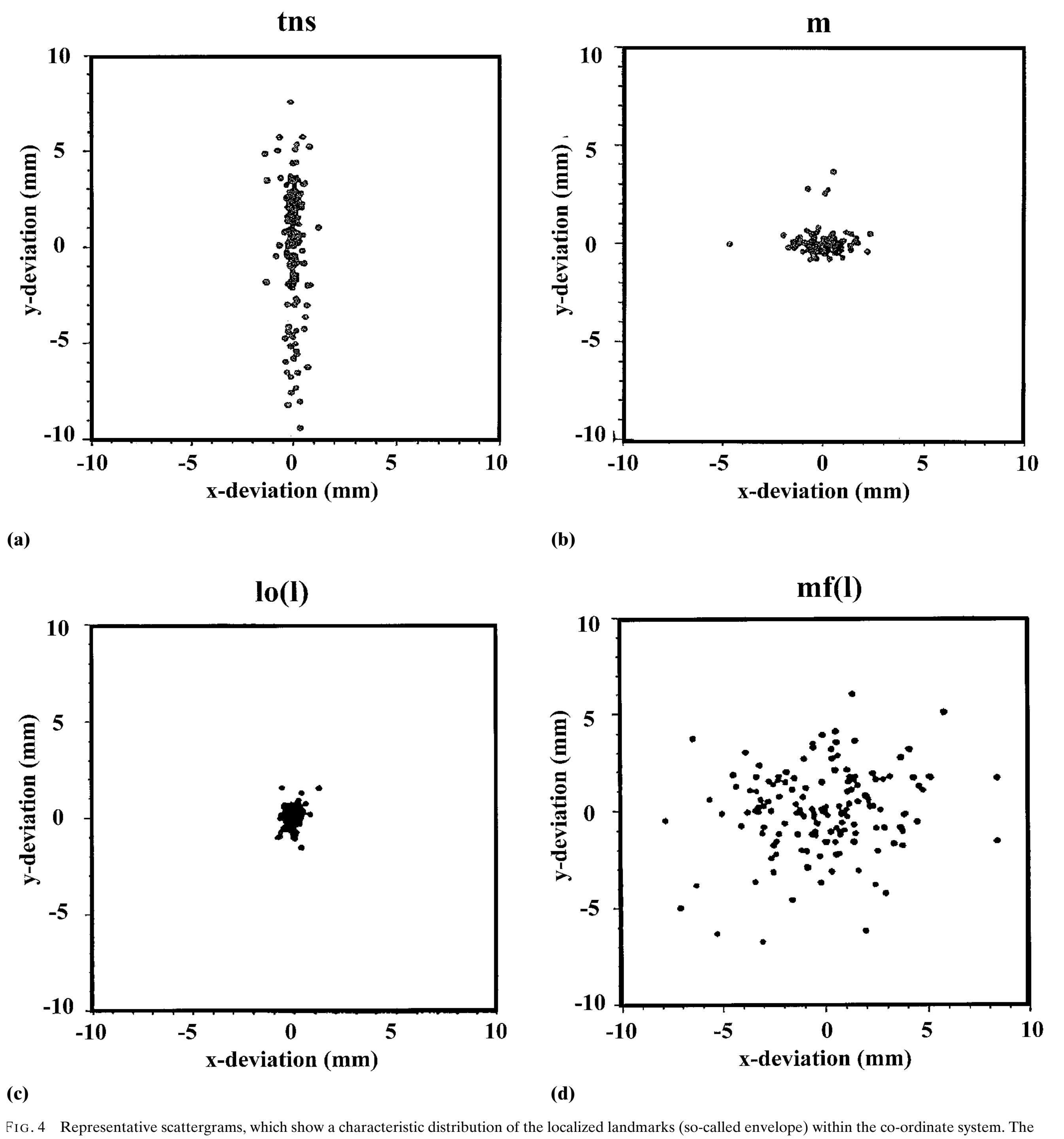

FIG. 4 Representative scattergrams, which show a characteristic distribution of the localized landmarks (so-called envelope) within the co-ordinate system. The envelope of the top of the nasal septum (tns) (a) is distinctively orientated vertically, whereas the envelope of the mandibular midpoint (m) (b) is orientated more in a horizontal direction. A very small, almost circular envelope is found for latero-orbitale left-sided [lo(l)] (c), whereas a large and diffuse envelope is found for mental foramen left-sided [mf(l)] (d); the envelopes of the contralateral landmarks are mirror images (Van der Meij, 1995).

Interestingly, the identification of the landmark zygomatic arch is rather controversial. The scattergram shows a very small, circular centre of 2·0 mm, which contains 90 per cent of the localized points, whereas a group of 10 per cent diffuse outliners results in ranges of 12·0 and 14·0 mm for the *X* and *Y* direction, respectively (Fig. 8). However, these outliners are not produced by only one examiner, indicating that this high range may be caused by the image quality of the zygomatic key ridge process on certain cephalograms.

Generally, the localized landmarks are distributed along the edges of the underlying anatomical structure and, without further elaboration, the envelope reflects the accuracy with which some landmarks can be located (Baumrind and Frantz, 1971).

Scattergrams deriving from the same landmarks, bilater-

TABLE 2 Cumulative listing of percentages of errors equal to or greater than specified values, in X and Y direction (mm), ranked according to the magnitude of overall mean vector |V|

Landmark	*X* 0·5	*Y* 0·5	*X* 1	*Y* 1	*X* 2	*Y* 2	*X* 3	*Y* 3	*X* 4	*Y* 4	*X* 5	*Y* 5	*X* 6	*Y* 6
ma (r)	25	8	1	1										
lo (l)	6	27	1	4										
ma (l)	27	7	8	1	1									
lo (r)	8	26	1	8		3		1						
ag (l)	25	23	7	5	2	1								
ag (r)	34	25	9	7	2	1								
om	30	28	10	4	1	1		1						
m	45	13	13	3	2	3	1	1		1				
lzmf (r)	17	62	5	21	1	11	1	3		1				
lzmf (l)	12	37	5	20	1	9	1	5		1				
mzmf (l)	15	57	2	27		7		1						
za (l)	23	41	15	16	5	5	4	3	2	2	1	1	1	1
za (r)	20	52	14	19	3	7	2	3	2	2	2	1	1	1
mzmf (r)	23	65	4	33		12		3		1				
lpa (r)	23	64	7	41	1	13		5		1				
lpa (l)	31	66	6	40		13		3						
ans	11	74	1	49		20		5		2				
mx (l)	35	67	13	43	1	19	1	10		5		2		1
isf	29	65	9	39	3	15	1	11		5		2		1
mo (l)	33	72	11	49	2	19		5		2		1		
mx (r)	39	65	13	45	2	21		9		5		1		1
mo (r)	43	72	12	54	1	17		7		1		1		1
iif	31	71	11	44	5	21	1	11		5		4		3
um (l)	61	66	33	37	17	14	3	5		3		1		1
lm (l)	63	63	31	41	15	15	5	5	3	3		3		1
um (r)	61	65	42	42	23	13	6	6	1	3		2		1
lm (r)	70	69	41	40	21	16	13	8	7	4	5	3	1	1
tns	13	87	3	72		53		32		22		15		7
cor (r)	61	89	32	76	9	55	3	35	1	20	1	16		10
mf (r)	77	75	65	55	47	29	29	19	17	7	10	4	6	1
mf (l)	87	77	71	62	48	28	29	17	13	6	8	3	4	3
cd (l)	85	80	67	63	42	43	25	25	11	14	5	5	2	3
cd (r)	89	79	73	61	45	38	29	25	13	14	3	9	2	5
cor (l)	68	91	37	85	9	67	1	49		33		21		14

ally, distinctly exhibit a similar standard deviation in *X* and *Y* direction (envelope), which clearly indicates that each landmark has its specific accuracy of localization.

To quantify the accuracy that can be accomplished in localizing the different landmarks, standard deviations, which express the average distance of the localized points to the arithmetical mean, were calculated. Since they differ in the *X* and *Y* direction, they were calculated for both directions separately. Thus, a list of the most reliable landmarks in both directions may be created and used to develop a more accurate postero-anterior cephalometric analysis.

An overall assessment of localization accuracy that can be achieved is expressed by the magnitude of the common mean vector |*V*|. Significant differences in its magnitude were found. Therefore, the hypothesis that all landmarks on PAC can be identified with the same accuracy is rejected.

Significant differences between examiners were found for seven of the 34 landmarks. These seven included all six dental landmarks. However, there was no indication that certain examiners showed consistently greater deviations from the arithmetical mean than the others. This implies that the accuracy of localizing landmarks on PAC is only slightly affected by the examiner, if he/she has an acceptable level of education and experience. Overall, the hypothesis that various examiners localize landmarks on PAC with the same accuracy, can be accepted for 27 of the 34 landmarks.

The second part of the study (intra-examiner reliability), revealed only a slight tendency for some examiners to localize certain landmarks consistently away from the arithmetical mean. Furthermore, there was no indication that the examiners localized the selected landmarks more accurately after repetition. Therefore, the hypothesis of a so-called learning process for identifying landmarks in PAC can be rejected. This is in contrast to Miethke (1989) who showed for lateral cephalograms that the accuracy improved when the examiners localized landmarks for a second time.

Most of the existing PAC analyses are quantitative using linear measurements, angles, and ratios. In this context a few critical comments seem appropriate.

Ricketts *et al.* (1972) suggest an assessment of the maxillary and mandibular intermolar width. The present study, however, shows that the accuracy in identifying the respective landmarks, maxillary and mandibular molar (r) and (l), is very low.

Grummons and Kappeyne van de Coppello (1987) base their analysis on the construction of four horizontal lines. One of them is a line connecting both medial aspects of the

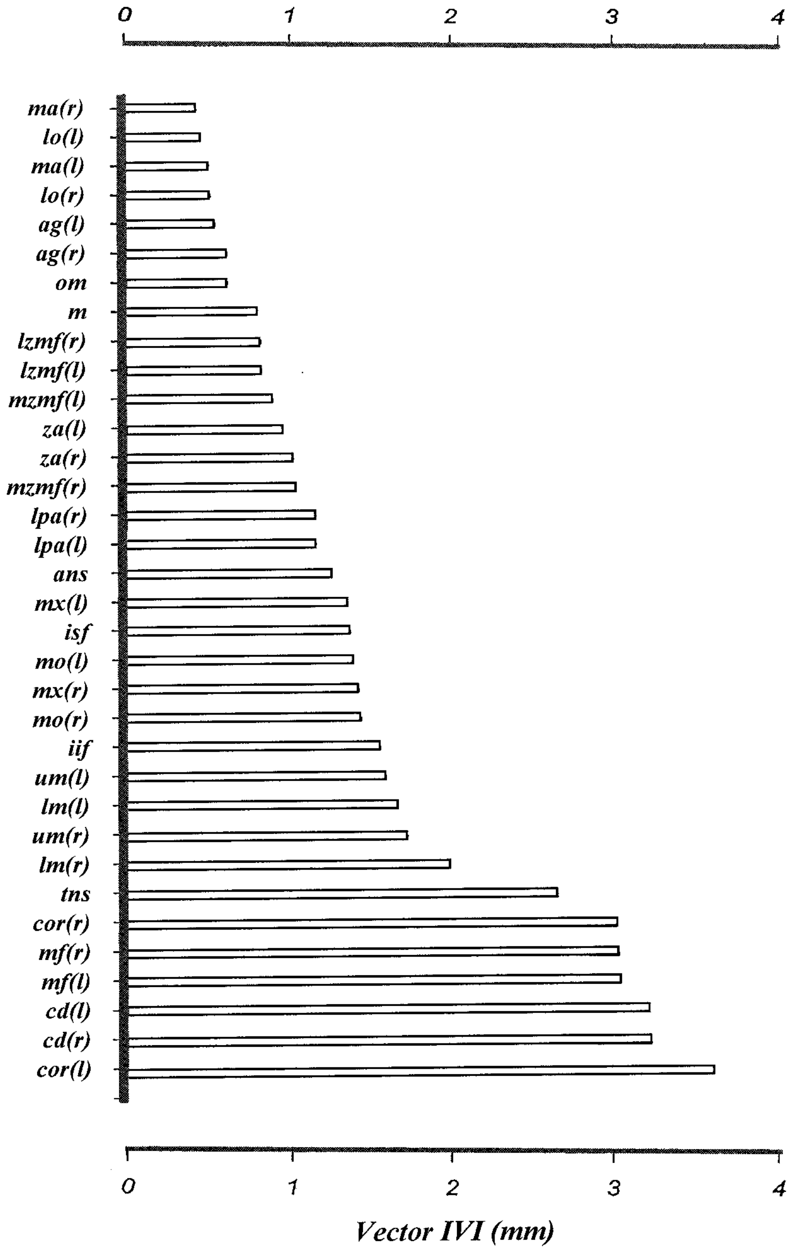

FIG. 5 The common mean vector |*V*| for all landmarks ranked according to their magnitude.

jugal processes. The localization of the respective landmark maxillare, is very unreliable in vertical direction according to the present study. Their evaluation of the mandibular morphology is based on the landmarks condylar (r) and (l), which again have a questionable localization accuracy. Furthermore, a vertical proportion analysis is performed, using the landmark anterior nasal spine, representing the vertical position of the maxillary complex. The present investigation shows clearly that this landmark is only reliable in a horizontal direction.

The above described limitations apply also for the analysis of Svanholt and Solow (1977).

In the qualitative analysis of Grayson *et al.* (1983) among other landmarks, coronoid process (r) and (l) [range in *Y* direction between 9·0 and 20·0 mm with a standard deviation exceeding 3·0 mm), condylar (r) and (l), and mental foramen (r) and (l) (range in *Y* direction 12·0 mm, range in *X* direction more than 15·0 mm; again, with a standard deviation of 3·0 mm] are used. This investigation proves that these three landmarks are the most unreliable, in both horizontal and vertical directions.

Conclusions

The present study has produced the following conclusions. The digitizing error is negligible compared to the landmark identification errors on PAC. Each PAC landmark has its

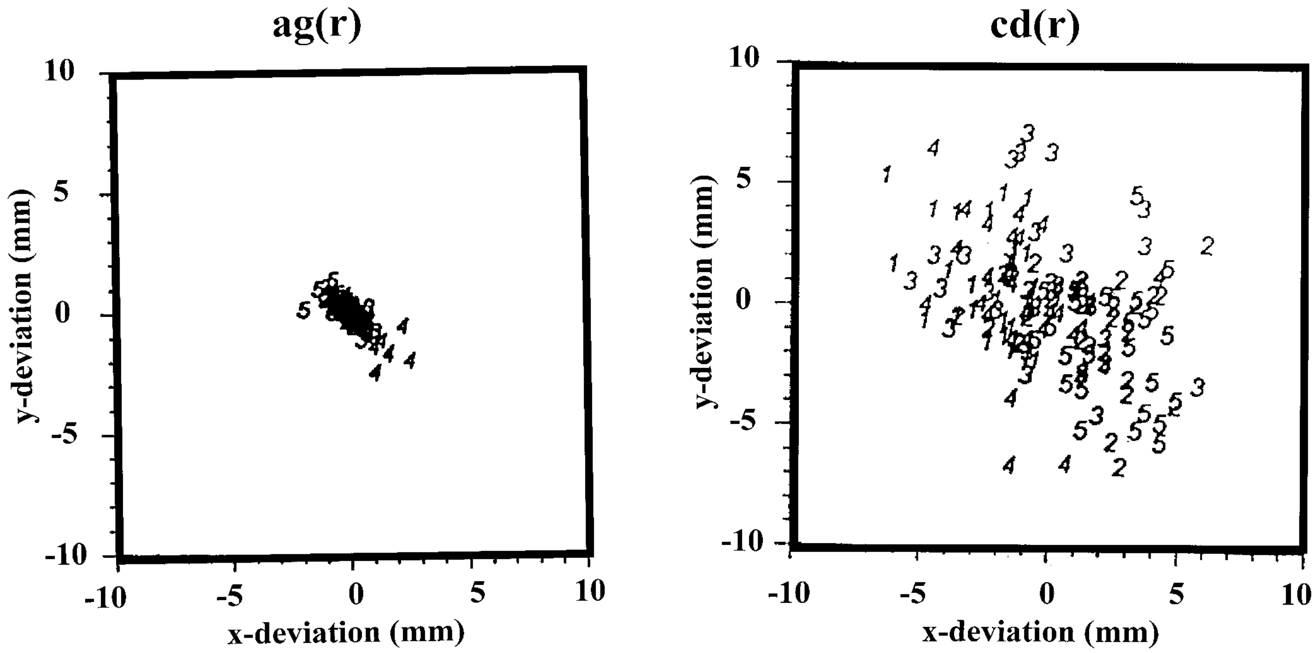

FIG. 6 Representative scattergrams that show the distribution of the localized landmarks (so-called envelope) within the co-ordinate system for the different examiners. The scattergrams of antegonion (r) [ag(r)] (a) reveals that examiners 4 and 5 localized these landmarks as distinctively different, although in an opposite direction, than their peers. A similar phenomenon, though with a larger range, is seen for landmark condylar (r) [cd(r)] (b), where the points of examiner 1 are localized more towards the negative *X* values, whereas the points localized by examiner 5 have mainly positive *X* values.

TABLE 3 *Standard deviation in X and Y direction (mm), per landmark, for the five examiners (1–5)*

Landmark	Exam. 1 *X*/*Y*	Exam. 2 *X*/*Y*	Exam. 3 *X*/*Y*	Exam. 4 *X*/*Y*	Exam. 5 *X*/*Y*
ag (r)	0·38/0·31	0·38/0·34	0·38/0·35	0·66/0·66	0·53/0·41
ag (l)	0·36/0·34	0·26/0·34	0·61/0·51	0·49/0·62	0·52/0·39
ans	0·40/1·28	0·22/0·92	0·32/1·31	0·38/1·22	0·23/0·59
cd (r)	1·72/2·10	2·39/2·21	2·53/2·86	1·93/2·89	1·58/2·37
cd (l)	1·83/2·15	2·40/2·39	2·25/2·91	1·88/2·93	2·19/2·25
cor (r)	1·51/2·49	1·36/2·62	1·10/3·60	1·07/2·48	0·84/2·59
cor (l)	1·08/3·13	1·27/2·61	1·14/3·77	0·92/3·13	1·09/2·40
iif	0·91/1·35	1·10/3·03	0·67/1·26	0·59/1·18	0·62/1·26
isf	0·73/1·24	1·20/2·90	0·36/0·95	0·48/0·96	0·37/0·98
lpa (r)	0·45/1·21	0·78/1·42	0·58/0·93	0·44/1·02	0·39/0·88
lpa (l)	0·47/1·16	0·48/1·15	0·43/1·11	0·45/1·10	0·45/1·21
lo (r)	0·34/0·69	0·24/0·55	0·26/0·73	0·39/0·73	0·22/0·53
lo (l)	0·16/0·47	0·23/0·40	0·28/0·55	0·40/0·60	0·23/0·38
m	0·87/0·58	0·83/0·68	0·65/2·17	0·59/0·57	0·97/0·53
lm (r)	1·30/0·94	1·66/2·20	1·95/1·51	1·77/1·71	1·54/0·94
lm (l)	0·59/0·86	1·12/1·98	0·81/0·81	1·53/1·59	0·75/0·93
ma (r)	0·32/0·21	0·40/0·26	0·40/0·17	0·42/0·31	0·30/0·34
ma (l)	0·32/0·19	0·59/0·32	0·60/0·18	0·55/0·30	0·54/0·25
mx (r)	0·53/1·42	0·67/1·82	0·55/1·86	0·88/1·65	0·63/1·36
mx (l)	0·52/1·41	0·53/1·34	0·66/1·91	1·03/1·85	0·72/1·59
um (r)	0·86/0·99	1·11/1·91	1·04/0·98	1·16/1·60	1·36/1·23
um (l)	0·87/0·83	0·85/1·67	0·70/0·91	0·98/1·30	1·11/1·05
mo (r)	0·32/1·56	0·43/1·31	0·51/1·81	0·45/1·24	0·45/1·25
mo (l)	0·48/1·54	0·71/1·27	0·40/1·62	0·48/1·22	0·54/1·15
mf (r)	2·82/1·95	2·74/1·79	3·28/2·21	2·59/2·38	2·52/2·44
mf (l)	2·65/1·90	1·92/1·84	3·00/2·27	2·41/2·44	3·03/2·31
om	0·50/0·43	0·46/0·28	0·57/0·71	0·44/2·64	0·55/0·38
za (r)	1·20/0·93	1·18/2·02	0·50/0·93	1·24/1·08	0·59/1·60
za (l)	1·09/0·68	1·54/1·81	0·57/1·09	1·10/0·87	0·87/1·49
tns	0·29/2·24	0·37/1·91	0·40/2·90	0·40/1·87	0·31/2·40
mzmf (r)	0·40/1·16	0·32/0·85	0·53/1·07	0·38/1·34	0·42/0·89
mzmf (l)	0·30/0·97	0·29/0·98	0·50/1·03	0·42/0·84	0·40/1·19
lzmf (r)	0·34/1·04	0·26/0·81	0·82/1·25	0·53/1·16	0·37/1·04
lzmf (l)	0·27/0·83	0·40/1·12	0·54/1·30	0·76/1·13	0·42/1·15

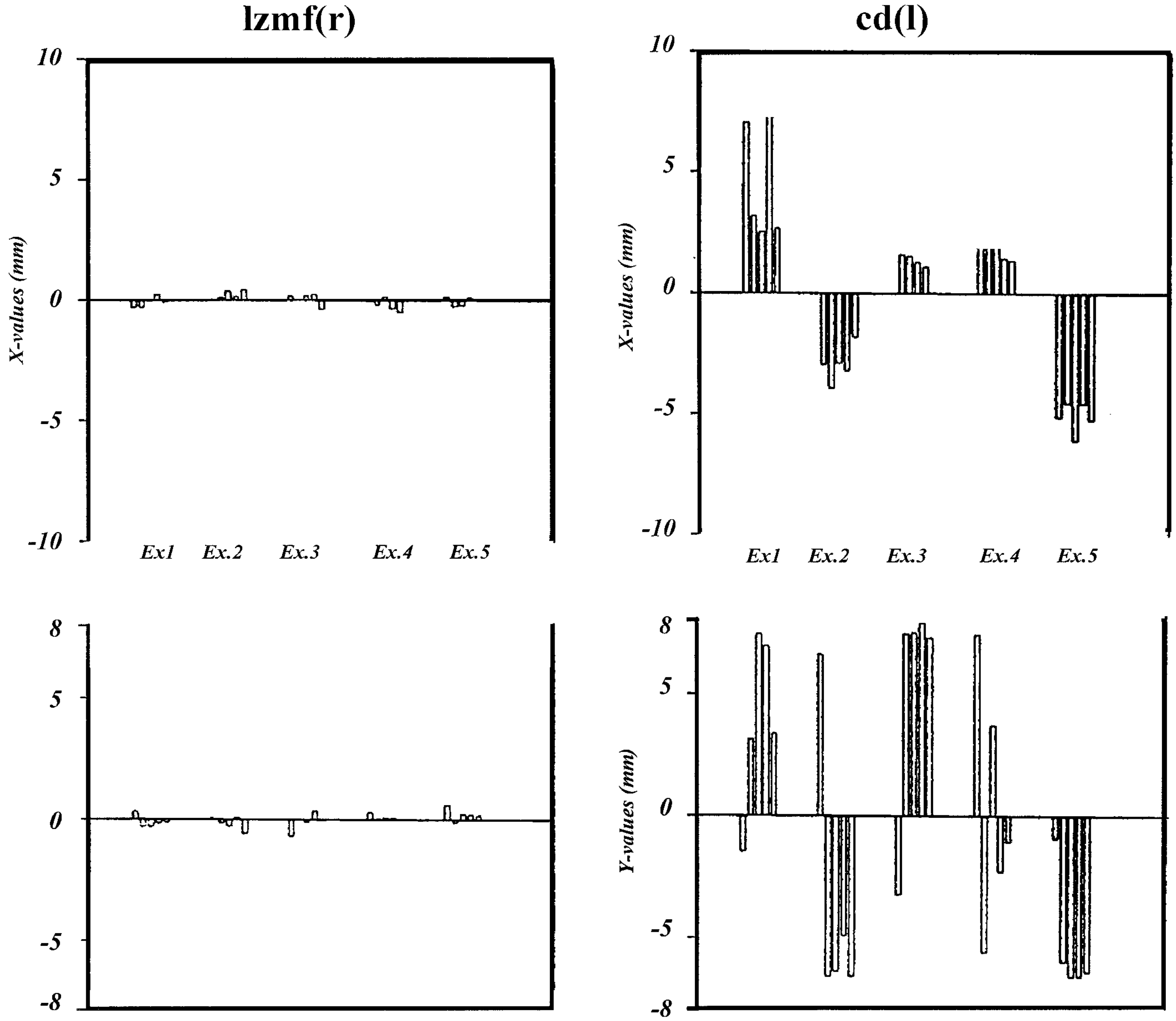

FIG. 7 Repeated localization of landmarks zygomaticofrontal lateral suture point-out (r) [lzmf(r)] (a) and condylar (l) [cd(l)] (b) revealing that the accuracy in landmark identification was virtually not subjected to a short-term learning effect.

TABLE 4 *Standard deviation, for all landmarks, per observer (1–5), in vector |V| direction (mm)*

Exam. 1	Exam. 2	Exam. 3	Exam. 4	Exam. 5
1·42	1·62	1·78	1·53	1·58

own characteristic envelope (distribution of localization random errors). Bilateral landmarks exhibit very similar (mirror image) envelopes. For most landmarks, there is a distinct difference in the localization accuracy between the *X* and *Y* direction. Overall, the accuracy of landmark identification differs significantly between the various PAC landmarks.

The six most accurate landmarks are mastoid (r) and (l), latero-orbitale (l) and (r), as well as antegonion (l) and (r); the six least accurate ones are coronoid (l) and (r), condylar (l) and (r), as well as mandibular foramen (l) and (r).

A significant difference in the accuracy of landmark identification between the five examiners of this study could be seen for seven of all 34 landmarks. However, there was no evidence that one examiner was consistently better/-worse than the others. Repeated landmark identification in the same PAC did not improve the accuracy, which excludes an immediate 'learning process'.

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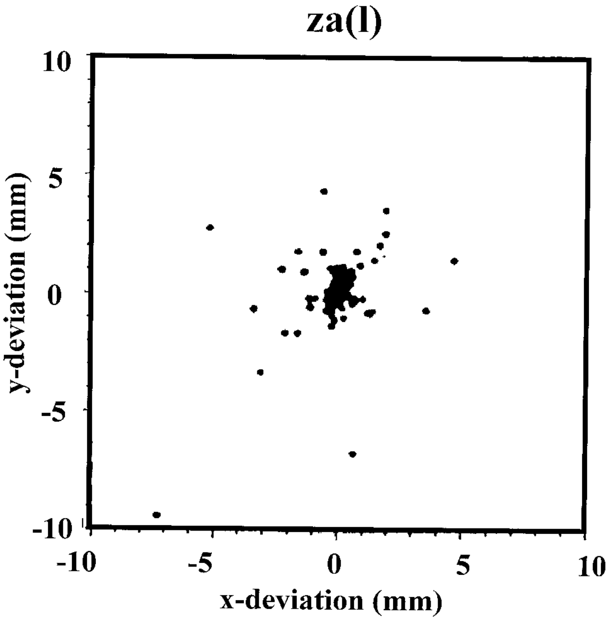

FIG. 8 The scattergram for the landmark zygomatic arch [za(l)] reveals a rather small, circular distribution of 2·0 mm, which contains 90 per cent of the localized points. However, a group of 10 per cent diffuse outliners results in ranges of 12 and 14 mm for the *X* and *Y* direction, respectively. The fact that these outliners are produced by all examiners, indicates that basically the accuracy of localization is related to the image quality of the zygomatic key ridge process on certain cephalograms.

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