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J DENT RES 1962 41: 672
DOI: 10.1177/00220345620410032101

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With the standardization of the technical procedure, radiography has become one of the most frequently applied aids in human biometric research. When using this method, it is necessary to make a careful check of the accuracy of the reproduction—for instance, with respect to enlargement and projection—since "hidden" errors can be incorporated into the radiographic image. In cephalometry, profile radiographs of the head have proved especially suitable for biometric purposes, since in such films the errors are small compared with those involved in other types of biometric registration. Former analyses of the accuracy of profile radiographs have been concerned with sources of error involved in the radiographic reproduction and with the accuracy of the measurement. There is, however, another problem that should be considered in this connection: the extent to which different procedures, by which measurements are made on the films, can affect the statistical analysis of these measurements, particularly in the case of the determination of correlation.

Two aspects of this problem are dealt with in this article. The first of these aspects relates to the measurement procedure itself, in which an examination is made of the extent to which errors incurred in marking reference points or lines on the films can affect the correlation between measurements involving these points or lines. The other aspect of the problem is whether the correlation coefficients differ according to whether the measurements are obtained directly from the film or indirectly by addition or subtraction of other measurements obtained directly.

Both these aspects are of particular interest, now that electronic data machines enable the calculation of practically unlimited numbers of correlation coefficients to be made and that combinations of measurements are easily obtained without entailing direct measurement.

EXPERIMENTAL METHODS

The interpretation of cranial radiographs of living subjects can involve a factor of uncertainty. This is especially true of details in the cranial base, the structure on which this analysis was based. For this reason, the study was made on crania from which the brain case had been removed, to permit inspection of the internal cranial base. Since, in buried crania, fragile bone structures, such as the coronoid processes and dorsum sellae, are often destroyed, the study was made on a collection of Indian crania

This investigation was supported by U.S.P.H.S. research grant D-843 from the National Institute of Dental Research, National Institutes of Health of the United States of America.

Presented on October 1, 1960, at the meeting of the Scandinavian Odontologic Society in Copenhagen.

Received for publication September 26, 1961.

that had not laid in the ground and in which even the most delicate structures were intact.

To eliminate errors in evaluating structures that often are not clearly visible on the radiograph, the mid-line of the cranial base was rendered more distinct by means of a 0.5-mm. lead thread and by painting with an aqueous suspension of tantalum powder (Fig. 1). Profile radiographs of the 101 adult crania of both sexes comprising the material were taken in a cephalostat.

The following reference points were employed (Figs. 2 and 3): basion (**ba**), the projection of the anterior border of the foramen magnum on a tangent through the lower contour of the foramen; ethmoidale (**eth**), the point on the cribriform plate of the ethmoid bone that is lowest in relation to the nasion-sella line (*NSL*); the point (**m**) on the medial crest of the anterior cranial fossa that lies immediately above the ethmoidale in relation to *NSL;* the nasion (**n**), the most anterior point of the naso-frontal suture; the point ($\mathbf{o}_1$) on the roof of the orbit that is highest in relation to *NSL;* the point ($\mathbf{o}_2$) of intersection between the contour of the roof of the orbit and the inner surface of the frontal bone; the pterygomaxillare (**pm**), the point of intersection between the dorsal contour of the maxilla and the nasal floor; the sella (**s**), the center of the bony crypt forming the sella turcica; and the spinal point (**sp**), the apex of the anterior nasal spine.

The following reference lines were then drawn: *NL,* the line passing through the points **sp** and **pm;** and O_1SL, O_2SL, *MSL, NSL,* and *ESL,* the lines connecting the points $\mathbf{o}_1$, $\mathbf{o}_2$, **m, n,** and **eth,** respectively, with point **s.**

Statistical analysis.—The analysis of correlation that this study was based on was performed with the aid of an electronic computer.* The term "correlation coefficient" as used here refers to the Brovais-Pearson coefficient of correlation,

$$r = \frac{s_{xy}}{\sqrt{(s_x^2 s_y^2)}}, \tag{1}$$

where s_x^2 and s_y^2 are the variances and s_{xy} is the covariance of the two variates x and y.

The theoretical distribution function for r is complicated, with a skew curve, the skewness increasing with r. In order to facilitate the statistical analysis of the correlation coefficients and to obtain a more accurate graphic comparison, the values of r were transformed to values of z, where $z = \frac{1}{2}[\log_e (1 + r) - \log_e (1 - r)]$. The distribution curve for the values of z is very nearly normal, and the values can therefore be treated by normal-curve methods.[1]

To express the relationship between the two series of values of z to be compared, the line of orthogonal regression was used. This line represents the average trend of the points on a regression diagram. Mathematically it represents the least sum of squares of the perpendicular distances to the line, unlike the lines representing the regression of y on x or of x on y, which represent the least sum of squares of the vertical and horizontal distances, respectively. The orthogonal regression coefficient, b, was obtained from the expression $b = \tan \alpha$, where

$$\tan 2\alpha = \frac{2\, s_{xy}}{s_x^2 - s_y^2}. \tag{2}$$

* DASK, Danish Institute of Computing Machinery.

Here x and y represent the two sets of values of z, s_{xy} is the covariance of the variates, and s_x^2 and s_y^2 are their variances.[2]

RESULTS

Part I: Measurements from films with and without marking.—Measurements are often performed directly on the film, after the various reference points have been marked by pinholes or, better, with a lead pencil. It is evident that any error incurred in marking a point will introduce an error into any measurement made from the point. This section is devoted to an examination of the extent to which such marking errors

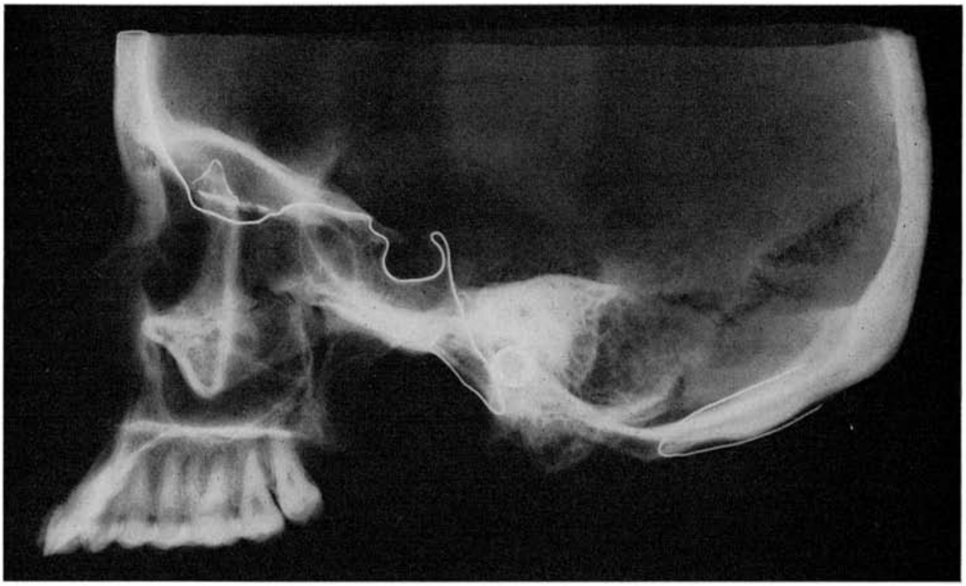


FIG. 1.—Profile radiograph of skull showing structures of the cranial base rendered more distinct by application of 0.5 mm. lead wire and by painting with a suspension of tantalum powder. Exposure data: 120 KV, 40 mA, 0.8 sec. Ferrania film without intensifying screens. Focus film distance 190 cm., film median plane of the head 10 cm.

affect the correlation coefficient. The underlying problem here is that if two angles have the vertex or one side in common, the marking error will be common to both of them, and the correlation coefficient will therefore increase. To test the importance of this source of error, the following experimental calculations were performed.

On each of the 101 radiographs, 11 angles were measured, first, without marking the points and then after the points had been marked with a lead pencil. These values will be referred to as Series A and Series B, respectively. All the values were obtained by measuring directly on the films.

The following procedure was used when performing the measurements on the film without marking the points. On two sheets of cellophane of the same dimensions as the film (24 × 30 cm.) lines were printed in two different ways. On one of them, a horizontal and a vertical line were printed along the mid-lines so as to form a cross. On the other sheet, parallel lines were printed 1 cm. apart. When measuring an angle, the two sheets were placed on the films so that the lines of the sheets formed the limbs of the angle. After one angle had been measured, the sheets were lifted and replaced for measuring of the next angle. By this procedure, systematic marking errors were avoided. It should be noted that a similar method, in which there is no marking of the reference points and lines, can be used for measuring linear distances. The 11 angular measurements that were used in this section of the study are listed in Table 1.

In the statistical analysis of the collected data, correlation coefficients were calculated for the 11 measurements in Series A taken in pairs, giving a total of 55 correlation coefficients (Table 2). These coefficients were transformed to values of z. Similar-

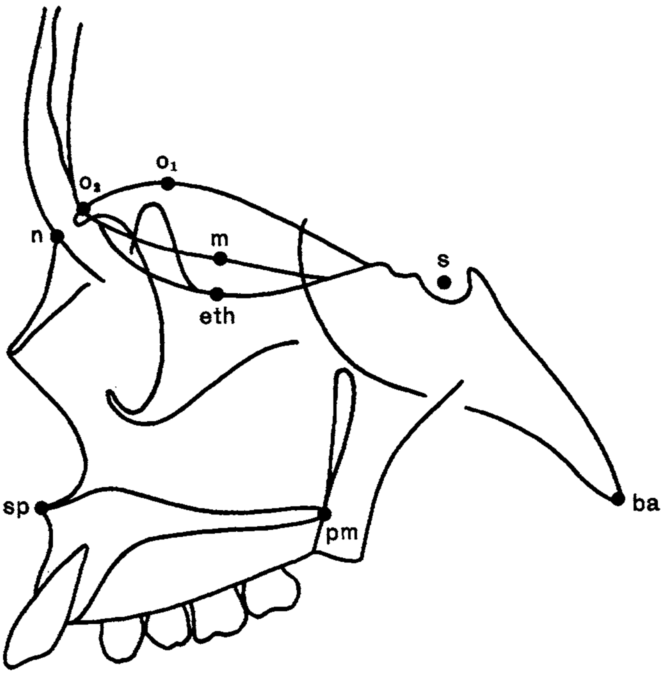


FIG. 2.—Reference points employed: Basion (*ba*) = the projection of the anterior border of the foramen magnum on a tangent through the lower contour of the foramen. Ethmoidale (*eth*) = the point on the cribriform plate of the ethmoid bone that is lowest in relation to *NSL*. The point (*m*) on the medial crest of the anterior cranial fossa that lies immediately above the ethmoidale in relation to *NSL*. Nasion (*n*) = the most anterior point of the nasofrontal suture. The point (o_1) on the roof of the orbit that is highest in relation to *NSL*. The point (o_2) = intersection between the contour of the roof of the orbit and the inner surface of the frontal bone. Pterygomaxillare (*pm*) = the point of intersection between the dorsal contour of the maxilla and the nasal floor. Sella (*s*) = the center of the bony crypt forming the sella turcica. Spinal point (*sp*) = the apex of the anterior nasal spine.

ly, 55 coefficients were obtained for the corresponding 11 measurements of Series B (Table 3), and these, too, were transformed to values of z. The two series of z-values were then compared graphically. Series A values were taken as the abscissas, and Series B values as the ordinates (Fig. 4). Negative pairs of values of z have been marked as positive values in this and the following graphs.

Each point in Figure 4 represents a pair of values of z, one from each series. If the values of z of the two series had been identical, the points would have been uniformly distributed about the diagonal of the graph, which has a slope of 45°. It was found, however, that most of the points lay above the diagonal. The deviation of the points from the diagonal line was found to be significant ($p < 0.001$) when tested by the χ^2 method. The slope of the orthogonal regression line representing the average trend of the points was 48°, which corresponded to an orthogonal regression coefficient, b, of

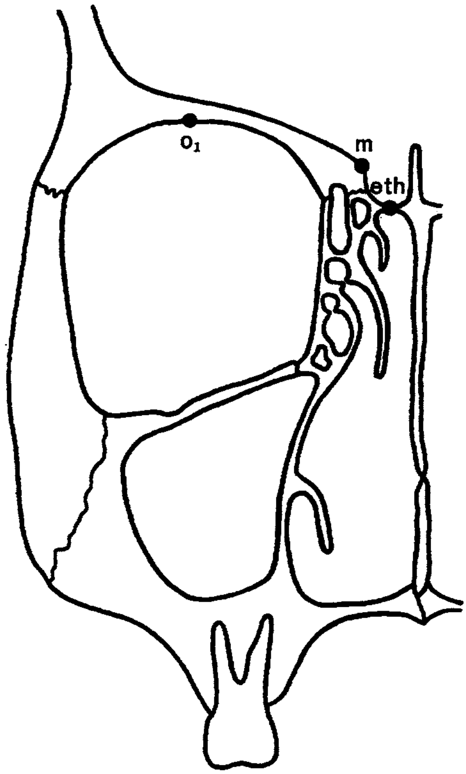


FIG. 3.—Frontal section of skull showing the location of points o_1, m, and *eth*. (Maxillary structure redrawn from P. Bellocq, *Le Squelette craniofacial* [Paris: Masson et Cie, 1958].)

TABLE 1

ANGLES MEASURED FIRST WITH AND THEN WITHOUT MARKING OF MEASURING POINTS

Angle No.	
1	**o_1—s—ba**
2	**o_2—s—ba**
3	**m—s—ba**
4	**n—s—ba**
5	**eth—s—ba**
6	*O_1SL/NL*
7	*O_2SL/NL*
8	*MSL/NL*
9	*NSL/NL*
10	*ESL/NL*
11	**e—s—n**

TABLE 2

CORRELATION COEFFICIENTS FOR ANGLES MEASURED WITHOUT MARKING OF MEASURING POINTS—SERIES A

No.*										
2........	.962									
3........	.783	.828								
4........	.908	.913	.756							
5........	.806	.840	.885	.754						
6........	.551	.487	.318	.391	.372					
7........	.461	.460	.318	.337	.326	.929				
8........	.191	.209	.452	.086	.348	.634	.707			
9........	.374	.347	.253	.415	.251	.808	.818	.612		
10........	.229	.228	.359	.121	.464	.720	.740	.837	.651	
11........	.228	.192	−.126	.399	−.266	.095	.062	−.340	.264	−.474
No*	1	2	3	4	5	6	7	8	9	10

* These numbers refer to angles entered in Table 1.

TABLE 3

CORRELATION COEFFICIENTS FOR ANGLES MEASURED WITH MARKING OF MEASURING POINTS—SERIES B

No.*										
2........	.971									
3........	.811	.849								
4........	.923	.938	.780							
5........	.803	.834	.921	.780						
6........	.554	.480	.389	.409	.354					
7........	.471	.466	.396	.371	.360	.950				
8........	.216	.220	.505	.131	.412	.706	.770			
9........	.443	.422	.344	.487	.316	.872	.889	.667		
10........	.223	.219	.429	.144	.495	.705	.765	.905	.678	
11........	.213	.196	−.175	.370	−.288	.095	.037	−.411	.281	−.509
No.*	1	2	3	4	5	6	7	8	9	10

* These numbers refer to angles entered in Table 1.

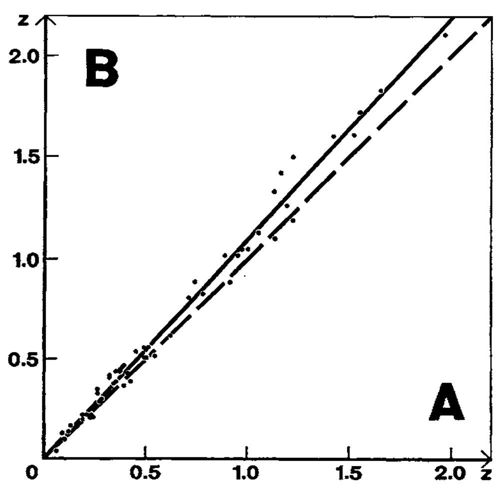


FIG. 4.—*Series B:* values of z calculated from correlations between pairs of angles measured *with* marking of the reference points on the radiograph. *Series A:* values of z calculated from correlations between the corresponding pairs of angles measured *without* marking of the reference points. ——— = orthogonal regression line, inclination 48°, regression coefficient, b, 1.10. - - - - = diagonal, inclination 45°, coefficient of inclination 1.00.

1.10. Hence the z-values of Series B were greater than those of Series A, and the deviation increased with increasing z-values of Series A.

The difference in the magnitude of the z-values and hence of the correlation coefficients of the two series could not be explained by a difference in the accuracy of the two methods of registration employed. The variances of the measurements in the two series did not differ in such a way as to explain the difference between the correlation coefficients of the two series. The sums of the variances in each of the series were almost identical, 213.66 in Series A and 217.23 in Series B. The accuracy of the registrations therefore even seems to be better without marking the points. As the marking errors, however, were correlated in Series B but not in Series A, the difference between the series of correlation coefficients may be explained by an artificial increase in the correlation coefficients of Series B, due to the marking of the measuring points.

TABLE 4

ANGLES MEASURED DIRECTLY OR DERIVED BY CALCULATION

Angles Measured Directly		Derivation of Calculated Angles			
No.		No.			
1	**o_1—s—ba**	15	**o_1—s—ba**	=angle No. 4+	angle No. 11
2	**o_2—s—ba**	16	**o_2—s—ba**	= 4+	12
3	**m—s—ba**	17	**m—s—ba**	= 4+	13
4	**n—s—ba**	18	**n—s—ba**	= 5+	14
5	**eth—s—ba**	19	**eth—s—ba**	= 4−	14
6	O_1SL/NL	20	O_1SL/NL	= 9+	11
7	O_2SL/NL	21	O_2SL/NL	= 9+	12
8	MSL/NL	22	MSL/NL	= 9+	13
9	NSL/NL	23	NSL/NL	= 10+	14
10	ESL/NL	24	ESL/NL	= 9−	14
11	**o_1—s—n**				
12	**o_2—s—n**				
13	**m—s—n**				
14	**n—s—e**				

Part II: Direct and indirect measurements.—In several fields of biometric research, it is the practice to derive certain measurements indirectly by the addition or subtraction of values yielded by direct measurements. One example of this in dental research is the spacing of the teeth, which can be obtained as the difference between the arch perimeter and the sum of the tooth widths. In the case of profile radiographs, too, it is tempting to save time by calculating values indirectly. For instance, the sagittal jaw relation can be obtained as the difference between the prognathic angles of the upper and lower jaws.

Indirect values will incorporate any errors in the values from which they are derived by addition or subtraction. The problem here is to what extent the coefficients of correlation for measurements derived indirectly differ from the coefficients for those obtained directly.

This possible source of error was analyzed on the basis of measurements performed on the profile radiographs of the 101 crania used in Part I. In conformity with the results of the previous analysis, only values obtained without marking the reference points were used in Part II. The angles used are given in Table 4. The first column gives the angles obtained by direct measurement, and the second column shows the way in which these angles were calculated indirectly by addition or subtraction.

Correlation coefficients were obtained from all the 24 angles taken in pairs. The matrix of these 276 coefficients is given in Table 5. For the analysis they were divided into four series—C through F—and a residual group, as shown in Table 5. The correlation coefficients in the four series were then transformed to values of z, and these were assigned to the corresponding Series C–F. This division was made because two different effects of indirect measurement on the coefficients must be distinguished in the analysis: (1) that which occurs when a part of the errors incurred in the measurements is common to both measurements to be correlated—for instance, if the measurements have part of an angle in common—and (2) the effect due to the error of measurement being greater for indirect than for the corresponding direct measurement. The residual group, consisting of 38 correlation coefficients, in which these two different effects are not clearly distinguished, was not included in the analysis.

The four series of z-values were composed as follows with respect to the combination of these factors: Series C—91 z-values, in which both angles were measured directly; Series D—20 z-values, in which one of the two angles was measured directly and the other indirectly and in which the former was used in the calculation of the latter; Series E—110 z-values, in which one of the two angles was measured directly and the other indirectly but in which the former was not used in the calculation of the latter; and Series F—17 z-values, in which both angles were measured indirectly and in which they had in common one angle used in the calculations.

Series C served as a control group, in which neither of the two effects to be examined influenced the correlation. It is obvious that the error of measurement was not common to any pairs of angles in Series C for which correlation coefficients were calculated, since all the angles were measured directly.

In Series D, on the other hand, the errors in the direct angles were included in the indirect angles with which they were correlated. An example taken from anthropometry might illustrate this. In correlating standing height and leg length, where the latter values are obtained indirectly as the difference between the standing and sitting heights, the error in determining standing height is incorporated in the leg-length measurements. To study the effect of this type of error on the correlation coefficients, the following calculations were performed.

In Figure 5 the 20 values of z composing Series D were taken as the ordinates and the corresponding 20 values in Series C as the abscissas. Each pair of values is represented by a point on the diagram. That the common errors of measurement affected the correlation coefficients was evident from the fact that the z-values of Series D were consistently larger than those of Series C, most of the points lying above the diagonal of the graph. This deviation was statistically significant ($p < 0.01$). The orthogonal regression line for the points had a slope of 48.5°, which corresponded to a coefficient, b, of 1.13.

The correlation between two angles, one of which was measured indirectly and the other directly, could thus be shown to be greater than that when both angles were measured directly. Hence indirect measurement of the angles could increase the correlation coefficient. This conclusion applied, however, only when errors of measurement were common to both the angles, as was illustrated by analysis of Series E.

TABLE 5

Correlation Coefficients for Angles Entered in Table 4*

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
2...	.962																						
3...	.783	.828																					
4...	.908	.913	.756																				
5...	.806	.840	.885	.754																			
6...	.551	.487	.318	.391	.372																		
7...	.461	.460	.318	.337	.326	.929																	
8...	.191	.209	.452	.086	.348	.634	.707																
9...	.375	.347	.253	.415	.251	.807	.817	.612															
10...	.231	.229	.360	.123	.466	.721	.739	.835	.650														
11...	.226	.169	.098	−.128	.136	.336	.283	.203	−.111	.185													
12...	.058	.115	.124	−.241	.125	.138	.231	.241	−.208	.186	.786												
13...	−.192	−.142	.270	−.372	.187	−.074	−.009	.530	−.211	.379	.383	.582											
14...	.228	.192	−.127	.400	−.265	.093	.059	−.344	.263	−.476	−.349	−.515	−.803										
15...	*.970*	.953	.773	**.920**	.786	.512	.439	.164	.359	.192	**.270**	.077	−.210	.250									
16...	.951	*.976*	.818	**.942**	.816	.448	.426	.171	.354	.190	.139	**.097**	−.181	.233	***.970***								
17...	.814	.853	*.961*	**.790**	.905	.356	.344	.440	.291	.378	.120	.134	**.275**	−.116	***.815***	***.857***							
18...	.921	.933	.783	*.975*	**.811**	.418	.353	.130	.403	.164	−.080	−.191	−.305	**.349**	*.915*	*.934*	*.809*						
19...	.820	.850	.887	**.809**	*.973*	.357	.321	.313	.273	.436	.087	.073	.119	**−.216**	***.820***	***.855***	***.916***	*.814*					
20...	.460	.405	.282	.308	.300	*.912*	.892	.663	**.847**	.688	**.434**	.233	.014	.052	***.470***	*.396*	*.328*	*.323*	*.295*				
21...	.396	.396	.308	.293	.306	.859	*.914*	.716	**.883**	.728	.268	**.275**	.072	.012	*.390*	***.395***	*.351*	*.305*	*.304*	***.944***			
22...	.163	.178	.416	.059	.350	.610	.668	*.910*	.665	.826	.201	.273	.590	−.397	*.136*	*.154*	***.450***	*.100*	*.317*	***.710***	***.784***		
23...	.440	.407	.280	.468	.277	.852	.843	.606	*.919*	**.672**	−.096	−.233	−.270	**.332**	*.417*	*.400*	*.307*	***.470***	*.286*	*.781*	*.791*	*.552*	
24...	.153	.157	.319	.057	.442	.635	.670	.799	**.674**	*.933*	.169	.212	.431	**−.535**	*.123*	*.132*	*.344*	*.085*	***.405***	***.701***	***.764***	***.886***	*.550*
No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23

* Series C: numbers *in frame* in roman lightface type; Series D: roman boldface type; Series E: roman lightface type; Series F: italic boldface type; Residual group: small italic lightface type.

Series E, like Series D, consisted of values of z obtained from one direct and one indirect angle, but with no common error of measurement. An example of this is the case in which the leg length is measured indirectly, as previously mentioned, and correlated with arm length measured directly. The result of this part of the analysis is shown in the diagram of Figure 6, where the 110 values of z composing Series E were the ordinates and the corresponding 110 values of Series C the abscissas. However, even if the number of points below the diagonal line was greater, the difference was small and not statistically significant. The orthogonal regression line for the points lay slightly below the diagonal of the diagram, with a slope of 44° and coefficient, b, 0.98. This tendency was in accord with the fact that the errors of measurement reduce the correlation coefficient.[3]

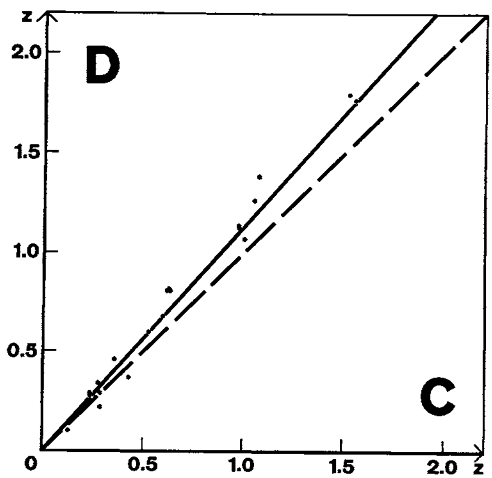


FIG. 5.—*Series D:* values of z calculated from correlations between pairs of angles, in which one of the angles was measured directly and the other indirectly and in which the former was used in the calculation of the latter. *Series C:* values of z calculated from correlations between the corresponding pairs of angles, both measured directly. ——— = orthogonal regression line, inclination 48.5°, regression coefficient, b, 1.13. - - - - = diagonal, inclination 45°, coefficient of inclination 1.00.

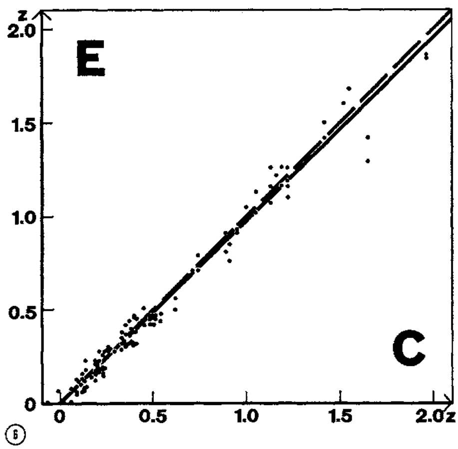
Of the two effects on the correlation of indirect measurements discussed, the first seems to be the stronger. They may act in opposite directions and can cancel each other out to some extent or reinforce each other. This was illustrated by Series F.

The correlation coefficients in Series F were calculated from values for two angles, both obtained indirectly. As the two angles had a part in common, the correlation coefficient was considerably increased. As both angles were obtained indirectly, the error of measurement was considerably increased, and this reduced the coefficient slightly at the same time. The combined effect was an increase in the correlation, since the former effect was the stronger. This is evident from Figure 7, where the 17 z-values of Series C are the ordinates and the corresponding 17 values of Series C are the abscissas. Most of the points lie above the diagonal, but, because of the small number of points, the deviation from the diagonal line was only probably significant ($p = 0.05$). The slope of the regression line was 49°, with a coefficient, b, of 1.15.

DISCUSSION

Among the possible sources of error in measurements on radiographs are the projection, the identification of the reference points, and the actual registration of the measurements. Such errors have been analyzed for profile radiographs by Björk[4] and many others. This paper deals with quite different sources of error, which have not previously been discussed—namely, the extent to which the registration procedure itself can affect the coefficients of correlation between such measurements.

In Part I it is proved that, by inserting lines or points on the radiographs, a false correlation may result for angles having a vertex or limb in common. To avoid this source of error, measurements on the films should be made without marking the reference points or lines. It can be shown that if the measurements are performed accurately, the registration errors are of the same order of magnitude, whether or not the reference points are marked in. That is to say, the standard deviations do not differ for the two methods. The increase in the correlation coefficients calculated for sets of measurements from marked points must therefore be due to the fact that the errors involved when marking the points are also correlated. This probably applies also to linear and all other kinds of measurements. When measuring on tracings, the systematic marking error is increased, so that a still larger false component can be expected in the correlation between such measurements.



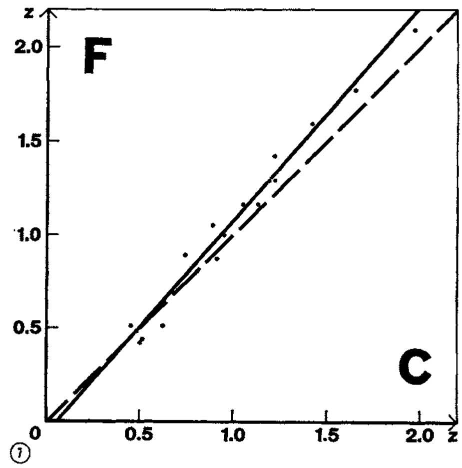


FIG. 6.—*Series E:* values of z calculated from correlations between pairs of angles, in which one of the angles was measured directly and the other indirectly and in which the former was not used in the calculation of the latter. *Series C:* values of z calculated from correlations between the corresponding pairs of angles, both measured directly. ——— = orthogonal regression line, inclination 44°, regression coefficient, b, 0.98. - - - - = diagonal, inclination 45°, coefficient of inclination 1.00.

FIG. 7.—*Series F:* values of z calculated from correlations between pairs of angles, in which both the angles were measured indirectly and in which they had in common one angle used in the calculations. *Series C:* values of z calculated from correlations between the coresponding pairs of angles, both measured directly. ——— = orthogonal regression line, inclination 49°, coefficient of regression, b, 1.15. - - - - = diagonal, inclination 45°, coefficient of inclination 1.00.

The method described for measuring without marking points is therefore recommended when the measurements are to be used for correlation analyses. If necessary, however, a mark can be made with a soft pencil and removed after each measurement.

In Part II the commonly used method of calculating the measurements indirectly as the difference between two other, direct, measurements is analyzed. Such indirect measurements are unsuitable for use in correlation analyses for two reasons: (1) when indirect measurements to be correlated have a dimension in common, the common registration errors are also correlated, which increases the correlation coefficient, and (2) when indirect measurements with no dimension in common are correlated, the coefficient may be reduced because indirect measurement usually involves a greater registration error. The former error seems to be the more powerful. The combined effect of the two sources of error on the coefficients may, however, not always be readily evident in a given case. For this reason, indirect measurements should, if possible, be avoided where correlation analysis is intended. These sources of error have to be considered when comparing correlation coefficients between measurements obtained by different procedures.

SUMMARY

A study was made to determine to what extent the manner of performing measurements on radiographs could affect the correlation between them. In Part I of the study the effect on the correlation coefficient of marking the reference points and lines on the film was investigated. It was found that the marking introduced a systematic error that increased the correlation coefficient. It was therefore concluded that all measurements to be used in correlation analyses should be made without marking reference points or lines. Such a method was described. In Part II the effect of using measurements obtained by the addition or subtraction of other measurements made directly on the film was studied. It was found that the use of such indirect measurements could, under certain conditions, cause an increase, and under other conditions a decrease, in the correlation coefficient. The conclusion was drawn, therefore, that all measurements used in correlation analyses should be measured directly and should not be obtained by calculation from other values.

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