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Covariations in Craniofacial Measurements Caused by Artificial Deformations of the Cranial Vault

By

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Abstract The principal component analyses on the craniofacial measurements of artificially deformed and undeformed skulls from the North Pacific coast of North America showed that some of the covariations in the craniofacial measurements tended to be caused or ceased by artificial deformations. It was consistently suggested from both male and female samples that while the anteroposterior and conical compressions of the cranial vault had little influence on the facial structure, they increased the variations of some neurocranial measurements, especially of parietal chord, together with those of maximum cranial length and breadth. This consistent pattern of covariation implies the existence of a mechanism for coordinating the development of parts of the craniofacial structure in response to external mechanical factors.

Artificial deformations of the neurocranium can be regarded as a kind of experiment on physical characters of the human body. We may be able to utilize the results of such an experiment for understanding the way of organic response to external stresses and a coordinating mechanism among regions of the body through the ontogenetic processes. In fact, there have been many investigations on the effects of the artificial cranial deformations (MACCURDY, 1923; OETTEKING, 1930; MCNEILL and NEWTON, 1965; OSSENBERG, 1970; EL-NAJJAR and DAWSON, 1977; HANZEL, 1977; GOTTLIEB, 1978; SCHENDEL *et al.*, 1980; DROESSLER, 1981; ANTON, 1989). Most of them are primarily based on the univariate comparisons, but HANZEL (1977) and DROESSLER (1981) carried out the principal component analysis for the pooled sample of deformed and undeformed crania and the comparisons of multivariate biological distances, respectively. In the present study, the problem of how the artificial deformations of the cranial vault cause extra variations/covariations in various regions of the craniofacial structure was re-examined by using a multivariate statistical analysis in a different way from those of the previous authors. Untill now, fortunately, MACCURDY (1923), OETTEKING (1930), DROESSLER (1981) and others have published a great deal of raw data on deformed skulls. In the present study, OETTEKING's (1930) data were used for carrying out the analysis.

Materials

OETTEKING (1930) exhaustively investigated the skeletal materials, including both deformed and undeformed skulls, from the North Pacific coast of North America which had been collected by the various members of the Jesup Expedition by 1913, and published all the raw data of the craniofacial measurements. He firstly grouped the entire skull material into four divisions: the undeformed, the Cowichan deformation, the Chinook deformation and the Koskimo deformation. Of the three deformation series, the Cowichan and Chinook represent the anteroposterior deformation, and the Koskino series shows the conical deformation. According to OETTEKING (1930), the anteroposterior type of intentional deformation is characterized by the condition that both the frontal and occipital regions are flattened, while the parietals are expanded in a sideward direction. On the other hand, the conical type is represented by the head whose superior-posterior view is rounded and whose vertex and the region posterior of it extrude upward and backward.

The undeformed specimens measured by OETTEKING (1930) were, in fact, not only of the North American Indians but also of the Inuits and Chukchee. On the other hand, the three deformation series came from the North Pacific coast of North America. Since it was desirable for the subjects of the present statistical analyses to be of the same genetical origin, the members of the undeformed skull series were also chosen out of the American Indians in the North Pacific coast: the Haida (Queen Charlotte Islands) and the Salish tribes of the Interior (Lillooet, Nicola Lake, Spences Bridge, Lytton, and Kamloops).

From each of the above four series, only the skulls measurable at least for the eighteen craniofacial measurement items shown in Tables 1 and 2 were further selected to carry out the multivariate statistical analyses. In result, the sample sizes of the undeformed skull series were reduced to 23 for males and 17 for females. Similarly, the sample sizes of the deformation series became as follows: 55 and 13 for the males and females, respectively, of the Cowichan; 51 and 22 for the Chinook; and 92 and 30 for the Koskimo.

Methods

Two approaches were adopted here to identify the covariations produced by artificial deformations in a system of craniofacial measurements. Both of them are based on the principal component analysis (LAWLEY and MAXWELL, 1963; OKUNO *et al.*, 1971, 1976; TAKEUCHI and YANAI, 1972). The principal component analysis was used to exclude the influence of a general size factor from the system of craniofacial measurements, that is, to readily detect the covariations due to artificial deformations even though they were faint compared with the covariations due to the general size factor. The two approaches are as follows.

1) Find large differences between the two principal components which are obtained from the two separate principal component analyses for an undeformed and a deformed skull series and represent a similar pattern of the factor loadings.

Table 1. Means and standard deviations of the linear measurements in the intact skulls with or without artificial deformations of American Indian males from the North Pacific coast of North America.

	Undeformed skulls (n=23)		Deformed skulls: Cowichan (n=55)		Chinook (n=51)		Koskimo (n=92)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Cranial length	182.4	8.7	169.3	7.1	166.3	5.5	183.3	6.5
Cranial breadth	144.2	4.4	152.7	8.6	156.1	6.5	139.7	5.9
ba-b height	134.7	7.0	131.4	6.3	128.8	6.4	131.9	5.0
Frontal chord	112.2	6.5	111.4	4.5	112.5	4.5	115.2	4.8
Parietal chord	105.6	8.8	94.9	5.7	91.1	6.8	105.0	5.4
Occipital chord	99.1	6.6	95.3	6.8	98.6	4.9	102.2	7.2
Cranial base length	103.9	4.5	99.3	5.2	98.8	4.0	100.7	3.6
Foramen magnum length	35.4	2.1	34.3	2.8	34.3	2.1	34.6	2.1
Foramen magnum width	30.1	2.7	29.7	2.5	30.5	1.9	29.8	1.8
Facial length	102.8	5.3	102.1	5.1	102.2	5.1	100.9	4.4
Upper facial height	74.6	3.4	73.2	4.7	73.5	3.4	76.7	4.8
Bizygomatic breadth	141.6	5.8	143.6	7.8	141.4	5.1	138.7	5.9
Orbital breadth (*mf-ek*)	45.0	2.0	43.4	2.1	43.5	1.5	44.4	2.1
Orbital height	35.8	1.8	36.1	1.9	36.1	1.5	37.7	1.8
Nasal breadth	25.8	2.1	24.6	1.9	23.9	1.8	24.0	1.7
Nasal height	52.2	2.8	52.1	3.9	53.4	2.6	54.1	2.9
Maxillo-alveolar length	54.6	3.1	54.5	3.1	54.2	2.8	54.2	2.9
Maxillo-alveolar breadth	66.8	2.9	64.2	4.1	66.5	3.2	65.2	3.8

2) Extract the principal components which are highly correlated with the cranial measurements that are considered to be directly affected by artificial deformations, e.g., maximum cranial length and breadth, from the principal component analysis of the between-group covariance matrix for all the deformed and undeformed skull series.

The between-group covariance matrix for the undeformed series and the Cowichan, Chinook and Koskimo deformation series was obtained together with the mean within-group covariance matrix by applying TAKEUCHI and YANAI's (1972) dummy variable method to the correlation matrix which was in advance calculated from a pooled sample of the above four deformed and undeformed skull series. Incidentally, it should be noted that not only the between-group covariances but also the mean within-group covariances involve some influence of the artificial deformations.

In all the analyses of the present study, the data of males and females were separately dealt with in order to confirm the repeatability of the results. And, even when a sample size was less than the number of the variables to be dealt with in a principal component analysis, the analysis was carried out on the assumption that the former was large enough compared with the latter.

Table 2. Means and standard deviations of the linear measurements in the intact skulls with or without artificial deformations of American Indian females from the North Pacific coast of North America.

	Undeformed skulls ($n=17$)		Deformed skulls: Cowichan ($n=13$)		Deformed skulls: Chinook ($n=22$)		Deformed skulls: Koskimo ($n=30$)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Cranial length	168.9	5.2	161.4	9.0	159.8	4.8	175.0	5.5
Cranial breadth	137.9	5.0	144.5	7.8	150.1	6.9	134.4	4.4
ba-b height	128.9	7.2	125.1	5.7	121.2	7.4	126.9	5.1
Frontal chord	106.7	4.5	107.2	4.2	106.9	4.1	110.9	4.7
Parietal chord	102.9	5.7	87.6	8.9	87.4	4.0	99.2	6.8
Occipital chord	91.2	5.4	96.7	5.2	95.4	4.7	101.1	6.8
Cranial base length	97.4	3.4	95.6	3.0	92.7	5.6	96.4	3.1
Foramen magnum length	34.1	2.2	33.7	1.9	32.6	1.4	32.6	2.1
Foramen magnum width	28.8	1.9	29.4	1.8	28.9	1.9	28.3	1.9
Facial length	97.4	4.2	99.3	4.8	96.9	5.0	98.2	4.1
Upper facial height	69.2	5.2	70.4	4.6	69.5	3.9	73.3	3.8
Bizygomatic breadth	129.9	5.8	134.2	5.1	132.8	4.8	130.4	4.7
Orbital breadth (*mf-ek*)	41.2	1.8	42.7	1.7	41.8	2.1	42.6	2.0
Orbital height	34.1	2.0	36.5	1.4	36.2	1.9	36.7	1.8
Nasal breadth	24.1	1.9	24.1	1.4	22.4	1.6	23.2	1.7
Nasal height	48.3	2.1	49.7	2.7	49.6	3.0	50.6	2.5
Maxillo-alveolar length	51.4	3.3	52.9	2.5	50.6	3.0	51.9	3.4
Maxillo-alveolar breadth	61.5	4.2	61.5	3.1	63.0	2.5	62.4	2.9

The statistical calculations were executed with the mainframe, HITAC M-880/310 (VOS3/AS-JSS4) System, of the Computer Centre, the University of Tokyo. The PCAFPP program for the principal component analysis and TAKEUCHI and YANAI's dummy variable method was written in FORTRAN by the present author.

Results

The averages of craniofacial measurements in the original samples from the North Pacific coast of North America have already been reported by OETTEKING (1930). The means and standard deviations listed in Tables 1 and 2 are the results of the recalculation based only on the selected specimens, i.e., skulls measurable for the eighteen craniofacial measurement items analyzed here. These tables show several differences in the mean values among the undeformed and deformed skull groups as follows:

1) Of the three deformation groups, the Cowichan and the Chinook are very similar to each other compared with the Koskimo in most of the measurements. Simply speaking, the Chinook and the Koskimo groups have the extreme forms of the two different types of cranial deformations, i.e., the

Table 3. Principal component analysis of the correlation matrix on the linear measurements of undeformed skulls of American Indian males.[1)]

	Factor loadings						Total variance (%)
	PC I	II	III	IV	V	VI	
Cranial length	.90*	.18	−.02	−.07	.12	.04	85.4
Cranial breadth	−.28	.48*	.54*	.15	.00	.08	63.0
ba-b height	.63*	.25	−.48*	.13	−.28	−.07	79.6
Frontal chord	.65*	.53*	−.18	−.24	−.03	.04	79.6
Parietal chord	.62*	.19	−.21	−.10	−.65*	.06	91.2
Occipital chord	.35*	.10	−.13	.35*	.72*	.18	82.9
Cranial base length	.71*	−.03	.11	.29	.22	−.30*	74.1
Foramen magnum length	.38*	.22	.32*	.46*	−.28	.45*	78.2
Foramen magnum width	.35*	.54*	.01	.35*	−.10	−.18	58.5
Facial length	.69*	−.58*	.02	.24	.11	−.15	90.8
Upper facial height	.67*	.22	−.02	−.49*	.26	.14	83.0
Bizygomatic breadth	.37*	.27	.77*	.27	−.04	.02	87.8
Orbital breadth (*mf-ek*)	.37*	−.40*	.40*	−.06	.03	−.57*	79.2
Orbital height	−.11	.65*	.35*	−.17	−.12	−.39*	75.3
Nasal breadth	.14	−.63*	.55*	−.26	−.26	.01	84.6
Nasal height	.09	.61*	.31*	−.56*	.28	.06	87.6
Maxillo-alveolar length	.76*	−.41*	−.17	−.21	−.02	−.01	81.6
Maxillo-alveolar breadth	.43*	−.52*	.45*	−.17	−.02	.43*	86.6
Total contribution (%)	27.7	18.0	12.4	8.4	7.9	6.0	80.5
Cumulative proportion (%)	27.7	45.7	58.2	66.6	74.5	80.5	80.5

1) The sample consists of 23 individuals with the skull measurable for the relevant measurement items.

* Greater than 0.30 in absolute value.

anteroposterior deformation and the conical deformation types.

2) Cranial length is large in the Koskimo, small in the Chinook, and inbetween in the undeformed. To the contrary, cranial breadth is small in the Koskimo, large in the Chinook, and inbetween in the undeformed.
3) While basion-bregma (*ba-b*) height, the length of the foramen magnum and nasal breadth are large in the undeformed, they are small in both the Chinook and the Koskimo. To the contrary, orbital height is small in the undeformed, but large in the two deformation groups.
4) Parietal chord is smaller in the Chinook than in the undeformed or the Koskimo.

Generally speaking, large between-group variations seem to be restricted to the neurocranium.

In Tables 3 to 8, the results of the principal component analyses (PCAs) of the correlation matrices on the eighteen craniofacial measurements are shown with regard to the males and females of the undeformed, of the Chinook deformed and of the Koskimo deformed skull series, respectively. In the undeformed skull series (Tables 3 and 4), the principal components (PCs) which were most highly correlated with the

Table 4. Principal component analysis of the correlation matrix on the linear measurements of undeformed skulls of American Indian females.[1)]

	Factor loadings					Total variance (%)
	PC I	II	III	IV	V	
Cranial length	.75*	.27	−.28	−.15	.19	77.7
Cranial breadth	.52*	−.55*	−.19	−.28	.34*	81.1
ba-b height	.83*	.36*	−.14	.03	−.06	84.4
Frontal chord	.62*	.36*	−.45*	.05	−.34*	83.4
Parietal chord	.73*	−.22	−.43*	−.01	.06	76.5
Occipital chord	.50*	.36*	−.14	−.44*	−.08	59.8
Cranial base length	.75*	.43*	−.08	.09	−.02	76.5
Foramen magnum length	.21	−.01	.81*	−.31*	−.30	88.7
Foramen magnum width	.67*	−.37*	.06	−.19	−.34*	74.3
Facial length	.75*	−.18	.22	.24	−.26	76.7
Upper facial height	.79*	.24	.31*	−.01	.06	77.1
Bizygomatic breadth	.79*	−.34*	.19	.14	.34*	92.0
Orbital breadth (*mf-ek*)	.79*	−.25	.21	−.28	.21	84.8
Orbital height	.54*	.23	.21	.26	.63*	85.1
Nasal breadth	.30*	−.32*	−.02	.81*	−.17	87.3
Nasal height	.59*	.54*	.36*	.21	.02	82.0
Maxillo-alveolar length	.82*	−.14	−.05	.01	−.23	74.9
Maxillo-alveolar breadth	.82*	−.43*	−.09	−.03	−.17	88.9
Total contribution (%)	45.9	11.4	8.9	7.5	6.8	80.6
Cumulative proportion (%)	45.9	57.3	66.3	73.8	80.6	80.6

[1)] The sample consists of 17 individuals with the skull measurable for the relevant measurement items.

* Greater than 0.30 in absolute value.

three major dimensions of the neurocranium, i.e., maximum cranial length and breadth and *ba-b* height, were first picked out because the three dimensions seemed the most appropriate indices to grossly measure the degree of artificial cranial deformations. In result, two PCs were found to be highly correlated with the three dimensions. One of them was interpreted, on the basis of the variation pattern of the factor loadings, as a so-called general size factor (Fig. 1) and the other as a cranial breadth/height factor (Fig. 2) both in males and in females. Then the corresponding PCs to such two factors were sought in the results of the PCAs for the Chinook and the Koskimo deformed skull series similarly on the basis of the variation patterns of the factor loadings (Figs. 1 and 2).

In Fig. 1, the factor loadings of the general size factors from the male and female samples of undeformed skulls are compared with those from the Chinook deformed and Koskimo deformed skull series as well as those from the mean within-group covariance matrices based on the four samples mentioned above. Major differences among the general size factors are discernible in the factor loadings on cranial length and parietal chord. The factor loading on cranial length is low in the Chinook compared with that in the undeformed both for males and for females. In the case of

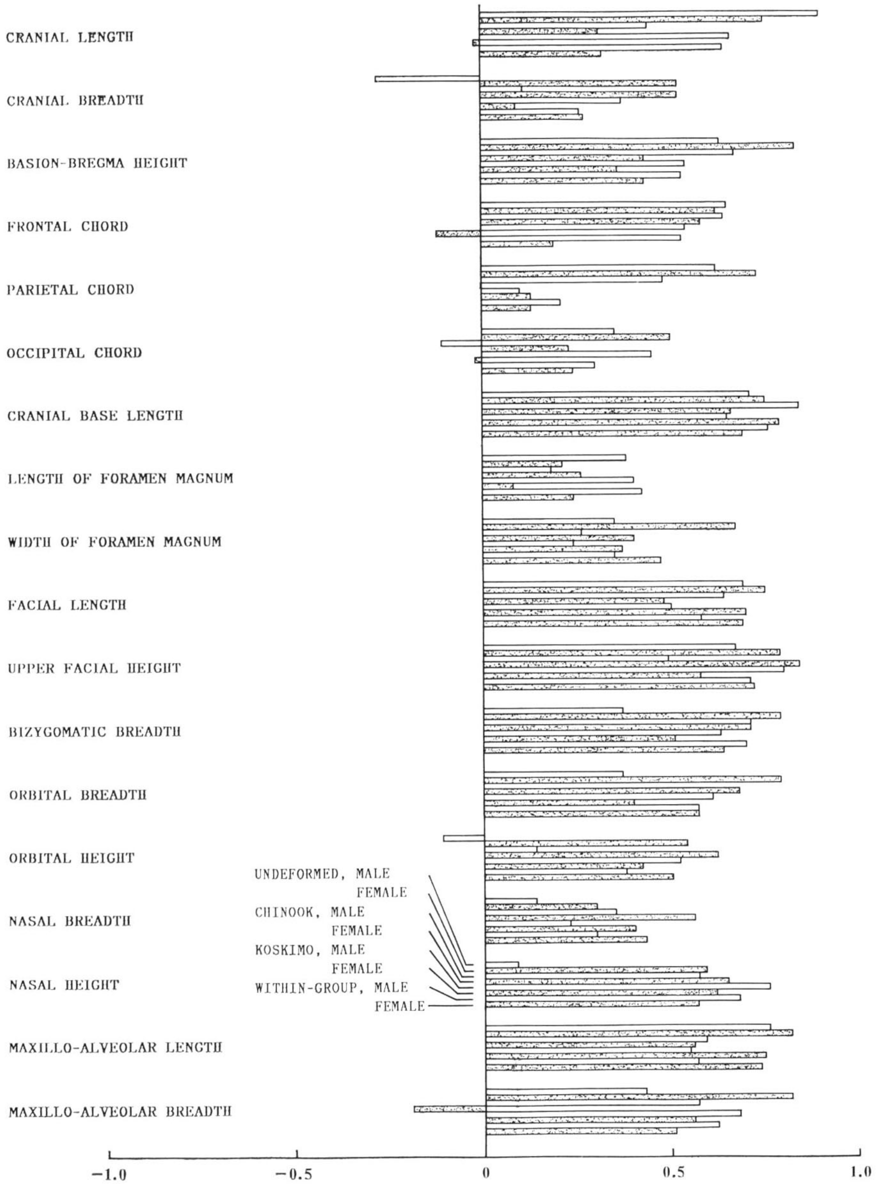

Fig. 1. Factor loadings of the general size factors on craniofacial measurements extracted from the individual samples of deformed or undeformed skulls. The factor loadings from the principal component analysis of the mean within-group covariance matrix were standardized by using the within-group total variances of the relevant characters.

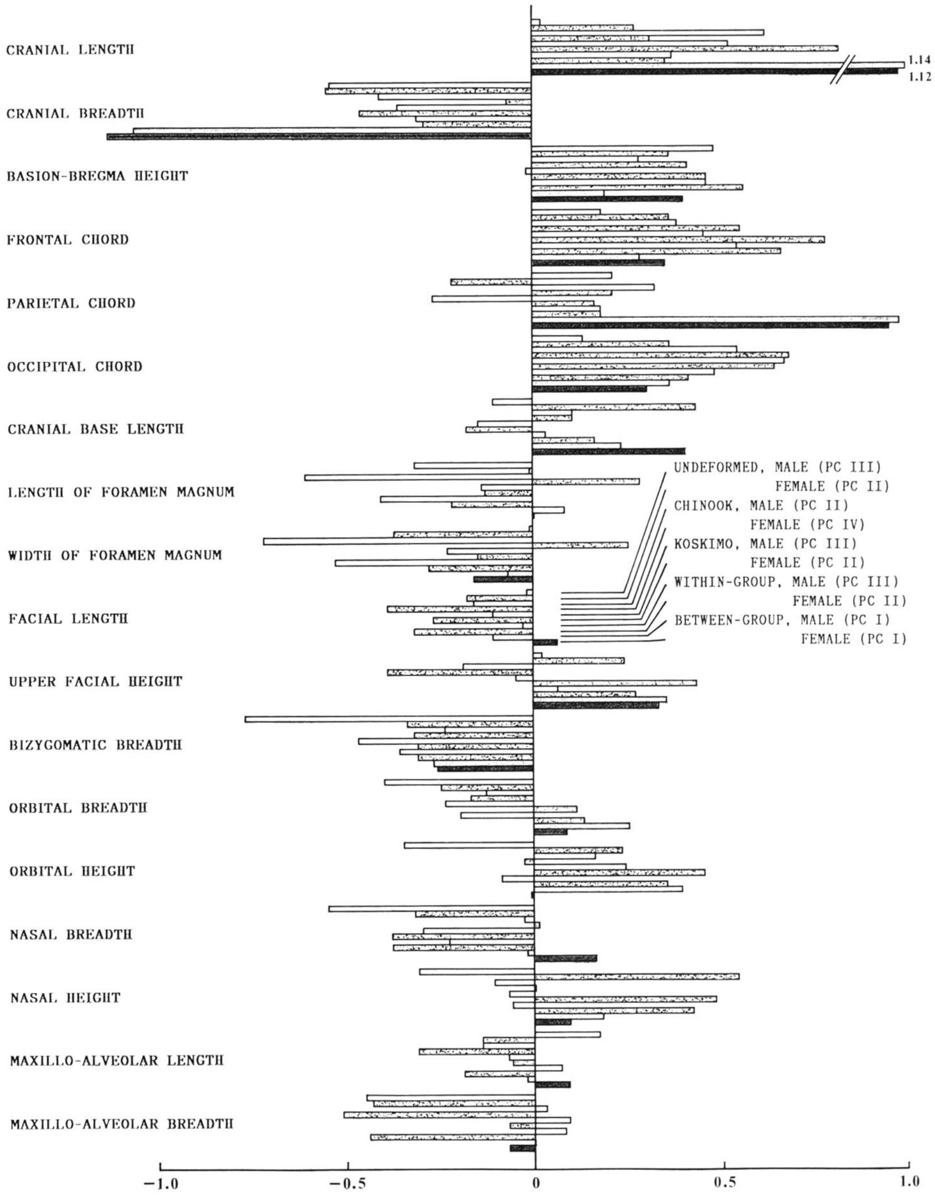

Fig. 2. Factor loadings of the principal components correlated mainly with the cranial vault extracted from the individual samples of deformed or undeformed skulls as well as those from the between-group covariance matrix constructed on the basis of the four samples of deformed and undeformed skulls. The factor loadings from the principal component analyses of the mean within-group and the between-group covariance matrices were standardized by using the within-group total variances of the relevant characters.

Table 5. Principal component analysis of the correlation matrix on the linear measurements of the skulls deformed in the Chinook mode of American Indian males.[1]

	Factor loadings								Total variance (%)
	PC I	II	III	IV	V	VI	VII	VIII	
Cranial length	.44*	−.62*	.08	.31*	−.07	.18	−.12	−.18	77.7
Cranial breadth	.11	.41*	.55*	−.55*	.18	−.13	−.21	.01	87.5
ba-b height	.67*	−.28	−.02	−.15	.44*	−.19	.21	−.03	82.1
Frontal chord	.64*	−.38*	.27	.02	.06	−.28	−.23	−.10	76.5
Parietal chord	.48*	−.32*	−.33*	.23	.48*	−.08	.15	−.07	76.2
Occipital chord	−.11	−.54*	.49*	−.23	.14	.22	.36*	.14	81.3
Cranial base length	.84*	−.10	−.28	−.08	−.06	.03	.09	−.18	85.2
Foramen magnum length	.18	.61*	−.08	.35*	.03	.39*	.36*	−.24	86.6
Foramen magnum width	.26	.72*	.00	.28	.32*	−.22	.10	.05	82.8
Facial length	.64*	.16	−.46*	−.39*	−.30*	.01	−.01	−.09	89.3
Upper facial height	.49*	.19	.41*	.43*	−.12	−.17	.10	.28	76.6
Bizygomatic breadth	.71*	.24	.30*	−.17	.05	.10	−.30	−.08	78.2
Orbital breadth (*mf-ek*)	.49*	.13	.50*	−.38*	−.07	.38*	.27	−.15	89.3
Orbital height	.14	−.16	.22	.26	−.75*	−.04	.11	.01	73.7
Nasal breadth	.35*	.03	−.18	.18	.16	.63*	−.44*	.22	86.1
Nasal height	.57*	.11	.32*	.55*	−.09	−.13	−.10	−.04	78.0
Maxillo-alveolar length	.59*	.14	−.35*	−.34*	−.36*	−.17	.04	.03	77.0
Maxillo-alveolar breadth	.57*	−.03	−.18	−.11	−.03	.08	.15	.65*	82.5
Total contribution (%)	25.8	12.5	10.4	9.9	8.0	5.9	4.8	4.2	81.5
Cumulative prop. (%)	25.8	38.3	48.7	58.6	66.6	72.5	77.3	81.5	81.5

[1] The sample consists of 51 individuals with the skull measurable for the relevant measurement items.

* Greater than 0.30 in absolute value.

parietal chord, the factor loading is lower in the Koskimo than in the undeformed.

As regards the cranial breadth/height factors (Fig. 2), the following tendencies common to both sexes are recognizable in their factor loadings. Namely, the factor loadings on cranial length and frontal chord are higher in the Koskimo than in the undeformed. The factor loadings on occipital chord has higher values in the Chinook and Koskimo than in the undeformed. On the other hand, the factor loadings on nasal breadth in the Chinook and those on maxillo-alveolar breadth in the Koskimo are lower than those in the undeformed.

In Tables 9 and 10 and in Fig. 2, the results of the PCAs of the between-group covariance matrices for males and females are shown. Here, again, the first PCs were picked out as what were most highly correlated with the three major cranial dimensions in the same way as in the PCAs for the individual samples. In Fig. 2, the factor loadings of the first PCs from the between-group covariances were standardized by using the within-group total variances of the relevant variables in order to compare the between-group and within-group PCs on the same scale. Conspicuous dif-

Table 6. Principal component analysis of the correlation matrix on the linear measurements of the skulls deformed in the Chinook mode of American Indian females.[1)]

	Factor loadings						Total variance (%)
	PC I	II	III	IV	V	VI	
Cranial length	.31*	.57*	.44*	−.31*	.37*	.04	84.7
Cranial breadth	.52*	.30	−.38*	.07	.39*	−.41*	82.9
ba-b height	.43*	−.58*	.17	−.41*	−.40*	−.10	89.2
Frontal chord	.58*	−.12	−.04	−.55*	.26	−.14	74.4
Parietal chord	−.00	−.48*	.62*	−.21	−.15	−.33*	78.6
Occipital chord	.23	.09	−.03	−.68*	.01	.63*	91.5
Cranial base length	.66*	−.44*	.29	−.10	.13	−.15	76.1
Foramen magnum length	.26	.78*	.24	−.28	−.18	−.29	92.7
Foramen magnum width	.40*	.69*	.16	−.25	−.38*	−.20	90.0
Facial length	.48*	−.18	.56*	.39*	.36*	.09	85.5
Upper facial height	.84*	−.06	−.14	.39*	−.07	.01	88.5
Bizygomatic breadth	.71*	.41*	−.18	.32*	−.10	.05	81.5
Orbital breadth (*mf-ek*)	.68*	−.26	−.21	.17	−.52*	.01	86.6
Orbital height	.62*	.14	−.57*	.03	−.15	.17	78.1
Nasal breadth	.56*	.19	.45*	−.01	−.01	.38*	70.0
Nasal height	.65*	−.25	−.45*	.00	.28	.00	76.5
Maxillo-alveolar length	.56*	−.25	.55*	.31*	.02	.10	78.8
Maxillo-alveolar breadth	−.19	.46*	.47*	.51*	−.17	.09	76.6
Total contribution (%)	27.7	16.3	14.3	11.1	7.1	5.8	82.3
Cumulative proportion (%)	27.7	44.0	58.3	69.4	76.5	82.3	82.3

[1)] The sample consists of 22 individuals with the skull measurable for the relevant measurement items.

* Greater than 0.30 in absolute value.

ferences between the between-group and the within-group PCs were found on three neurocranial measurements, i.e., cranial length, cranial breadth and parietal chord, both for males and for females (Fig. 2). The signs of the factor loadings of the between-group first PCs on the cranial breadth are however reverse to those on the other two measurements. It should further be noted here that the factor loadings of the between-group first PCs on upper facial height also have relatively high values, though not so high as in the cases of the above cranial length and parietal chord, in both males and females (Fig. 2).

Discussion

As stated by DINGWALL (1931), artificial cranial deformations are of two kinds: accidental or unintentional; and intentional. The deformed skulls analyzed here are considered those which were intentionally deformed by certain traditional methods (OETTEKING, 1930; DROESSLER, 1981). In the present study, they were, together with the undeformed materials, assumed to be of the same biological origin in the same geo-

Table 7. Principal component analysis of the correlation matrix on the linear measurements of the skulls deformed in the Koskimo mode of American Indian males.[1)]

	Factor loadings									Total variance (%)
	PC I	II	III	IV	V	VI	VII	VIII	IX	
Cranial length	.66*	−.11	.52*	−.03	−.11	.17	−.23	.29	.15	92.1
Cranial breadth	.37*	−.55*	−.36*	.30*	.26	−.18	.27	−.03	.06	83.7
ba-b height	.54*	−.32*	−.02	.12	.54*	.24	−.02	−.35*	−.07	89.0
Frontal chord	.54*	−.41*	.45*	−.05	.11	.07	.22	.07	−.13	74.6
Parietal chord	.10	−.49*	−.27	−.03	−.29	.68*	.04	.04	.33*	97.1
Occipital chord	.45*	−.02	.67*	.02	.32*	−.10	−.05	.17	.14	82.3
Cranial base length	.65*	.29	−.15	.03	.29	−.01	−.41*	−.21	.27	91.0
Foramen magnum length	.40*	.42*	−.14	.43*	−.02	.28	−.33*	.15	−.37*	88.5
Foramen magnum width	.24	.28	−.23	.65*	.04	.02	.29	.34*	.09	82.6
Facial length	.50*	.60*	−.11	−.21	.05	−.03	.16	−.22	.24	80.3
Upper facial height	.80*	−.11	−.05	.03	−.31*	−.13	.01	−.23	−.02	82.4
Bizygomatic breadth	.63*	−.18	−.47*	−.01	.18	−.13	−.14	.22	−.15	79.7
Orbital breadth (*mf-ek*)	.61*	−.08	−.24	−.22	−.08	−.37*	−.01	.29	.26	77.7
Orbital height	.52*	−.13	.24	.29	−.49*	−.21	.02	−.25	−.11	79.6
Nasal breadth	.23	−.28	−.30*	−.63*	−.01	−.01	−.16	.14	−.26	73.7
Nasal height	.76*	−.07	−.07	.10	−.39*	−.03	−.11	−.08	−.02	76.1
Maxillo-alveolar length	.55*	.53*	−.07	−.34*	−.05	.23	.28	.05	.01	83.4
Maxillo-alveolar breadth	.68*	.22	.09	−.23	.08	.14	.36*	−.01	−.29	81.5
Total contribution (%)	29.7	11.1	9.4	8.2	6.7	5.3	4.7	4.1	3.9	83.1
Cumulative proportion (%)	29.7	40.8	50.2	58.4	65.0	70.4	75.0	79.1	83.1	83.1

1) The sample consists of 92 individuals with the skull measurable for the relevant measurement items.

* Greater than 0.30 in absolute value.

Table 8. Principal component analysis of the correlation matrix on the linear measurements of the skulls deformed in the Koskimo mode of American Indian females.[1)]

	Factor loadings								Total variance (%)
	PC I	II	III	IV	V	VI	VII	VIII	
Cranial length	−.02	.82*	−.16	.25	−.06	−.22	−.04	.17	84.6
Cranial breadth	.09	−.46*	.10	.15	−.02	−.43*	.71*	−.04	93.8
ba-b height	.36*	.46*	−.09	−.27	.37*	−.26	.08	−.47*	85.6
Frontal chord	−.12	.78*	−.41*	.10	.02	−.13	.18	.08	85.9
Parietal chord	.13	.16	.41*	−.19	.75*	−.32*	−.15	.04	93.2
Occipital chord	−.02	.64*	−.55*	.13	−.22	−.17	−.03	−.08	81.0
Cranial base length	.79*	−.18	.05	−.26	−.11	−.06	−.19	−.16	80.3
Foramen magnum length	.08	−.13	.46*	.57*	−.38*	−.22	.02	−.38*	89.8
Foramen magnum width	.37*	−.15	−.02	.68*	.15	−.22	−.46*	.06	91.3
Facial length	.70*	−.27	−.44*	.07	−.10	.17	.03	.18	84.3
Upper facial height	.58*	.43*	.26	−.11	−.14	.28	.09	−.26	76.7
Bizygomatic breadth	.51*	−.31*	−.31*	−.07	−.16	−.49*	−.13	−.02	73.8
Orbital breadth (*mf-ek*)	.40*	.11	.50*	−.29	−.37*	−.20	−.10	.27	77.3
Orbital height	.42*	.45*	.46*	.04	−.03	−.07	.26	.42*	84.4
Nasal breadth	.40*	−.38*	−.46*	−.34*	−.02	−.22	.02	.20	73.0
Nasal height	.62*	.48*	.24	−.10	−.22	.16	−.06	−.04	75.5
Maxillo-alveolar length	.75*	−.06	−.35*	.16	.17	.32*	.20	−.13	89.0
Maxillo-alveolar breadth	.56*	−.07	.10	.45*	.44*	.23	.14	.17	82.8
Total contribution (%)	21.1	17.5	11.8	8.5	7.7	6.5	5.5	4.9	83.4
Cumulative prop. (%)	21.1	38.6	50.3	58.8	66.6	73.1	78.6	83.4	83.4

1) The sample consists of 30 individuals with the skull measurable for the relevant measurement items.

* Greater than 0.30 in absolute value.

graphical region and, therefore, to show only the variations due to such intentional deformations except for ordinary phenotypic variations between individuals within a population.

Univariate comparisons

The data used here are those obtained by OETTEKING (1930). According to him, the average of cranial capacity in his original materials gradually increases in the order, the undeformed, Cowichan, Chinook and Koskimo deformations at least in males, but the variation of the averages among the samples combined for sexes is restricted within the range between −1 and +1 standard deviation of the undeformed series. In marked contrast to this, the among-group variations in averages of crangial length and cranial breadth were shown to be very large. It was also recognized by him that foramen magnum length was smaller in the three deformation groups. These were confirmed also in the present study (Tables 1 and 2). As regards other conspicuous effects of artificial deformations, OETTEKING (1930) pointed out that KLAATSCH's central angle, i.e., the angle between the basion-bregma and the glabella-lambda lines, suffered the greater distortions in the deformed series in the order Cowichan-Koskimo-Chinook males and females combined; that the obliteration of main sutures on the cranial vault was retarded and the formation of wormian bones tended to increase in deformed skulls; and so on. He classified these changes into two types, direct and indirect ones, considering that distortions in the skull were caused not only by direct deformatory strain but also by indirect factors such as physiological adjustment of the disturbed conditions of cerebral growth and expansion and cranial equilibrium. Although the corroboration of his interpretation requires further systematic comparisons of morphological characters and physiological factors, the equilibrium or interaction of cranial characters can at least be confirmed through the multivariate analysis of cranial measurements as carried out in this study.

Principal component analyses

The general size factors for the skull extracted from the PCAs on the individual samples in the present study (Fig. 1) suggest that the cranial length and occipital chord of the Chinook deformation series and the parietal chord of the Koskimo are relatively independent of the respective general size factors. On the other hand, in the undeformed skull series, not only the cranial length but also the parietal and occipital chords have relatively high correlations with the general size factor (Fig. 1). These facts mean that artificial deformations break an ordinary equilibrium among portions of the skull and produce a new equilibrium through the process of its growth. In the new conditions, the factor which controls not only the cranial length and occipital chord but also frontal chord is predominant both in the Chinook and in the Koskimo deformation groups (Fig. 2). Although this factor may be called a cranial breadth/height factor in the undeformed skull group, it had better be named a frontal-and-occipital chord factor in the deformation groups. In summary, it is most likely that the artificial deformations of both anteroposterior and conical types cause the intragroup variations common to the frontal and occipital chords and, therefore, also to cranial length independently of the general size factor for the skull. Such inference cannot be drawn from univariate statistical analyses as performed by OETTEKING (1930).

On the other hand, the results of the PCA on the between-group covariances are substantially the same as those of the comparisons of the averages in the deformed and undeformed skull series obtained by OETTEKING (1930). The between-group first PC was found to be strongly correlated with cranial length and parietal chord and, at the same time, inversely correlated with cranial breadth (Fig. 2). Among the facial measurements analyzed, upper facial height appears to be somewhat correlated with this factor in the same way as the cranial length and parietal chord. It can be said, therefore, that the artificial deformations of the two kinds cause the between-group variations common to cranial length, parietal chord and upper facial height in the same direction and, simultaneously, the between-group variation of cranial breadth in the reverse direction.

Table 9. Principal component analyses of the within- and between-group covariance skull series of American

	Within-group								
	Factor loadings[2]								
	PC I	II	III	IV	V	VI	VII	VIII	IX
Cranial length	.42*	.08	.24	.00	−.06	−.00	.11	−.06	.01
Cranial breadth	.18	.17	−.21	−.10	.16	.23	−.24	.18	−.02
ba-b height	.51*	.11	.44*	.34*	.41*	−.14	−.08	−.03	.07
Frontal chord	.50*	.26	.51*	.03	.11	−.06	−.07	.15	−.02
Parietal chord	.15	−.03	.13	.07	.19	−.43*	−.07	.14	.05
Occipital chord	.28	.14	.44*	.14	−.03	.63*	.17	−.11	−.20
Cranial base length	.72*	−.18	.03	.18	.12	−.03	−.09	−.39*	.08
Foramen magnum length	.42*	.10	−.41*	.51*	−.09	−.07	.43*	−.12	.22
Foramen magnum width	.35*	.17	−.52*	.51*	.05	.12	−.18	.23	−.30
Facial length	.57*	−.66*	−.03	.07	−.17	.00	−.15	−.19	−.12
Upper facial height	.67*	.25	.06	−.16	−.30*	−.16	−.00	.07	−.15
Bizygomatic breadth	.67*	.12	−.34*	−.12	.29	.08	−.12	.03	.10
Orbital breadth (*mf-ek*)	.55*	−.06	−.19	−.39*	.11	.25	−.22	−.08	.31*
Orbital height	.34*	.46*	−.08	−.21	−.34*	−.06	−.00	−.19	.09
Nasal breadth	.28	−.15	−.22	−.45*	.46*	−.10	.42*	−.10	−.35*
Nasal height	.66*	.39*	−.06	−.17	−.21	−.20	−.02	−.02	−.17
Maxillo-alveolar length	.57*	−.62*	.07	−.00	−.26	−.05	−.07	.20	−.11
Maxillo-alveolar breadth	.60*	−.20	.08	−.11	−.06	.13	.34*	.45*	.26
Total variance	4.49	1.53	1.43	1.19	.93	.85	.72	.65	.58
Total contribution (%)	29.6	10.1	9.4	7.8	6.1	5.6	4.8	4.3	3.8
Cumulative proportion (%)	29.6	39.7	49.1	56.9	63.0	68.6	73.4	77.6	81.4

[1] A total number of individuals for the four series is 221.
[2] Covariances between the original variables and the standardized principal components.
* Greater than 0.30 in absolute value.

Taking both results of the within- and beween-group PCAs into account, it may be said that most measurements of the cranial vault except basi-bregmatic height, cranial base length, foramen magnum length and breadth are relatively systematically and coincidentally deformed through the anteroposterior and/or conical compression of the cranial vault, while most measurements of the facial structure except upper facial height hardly suffer the consistent influence of such deformations. In other words, such relatively consistent covariations in certain measurements appear to support the above-mentioned OETTEKING's (1930) consideration on the physiological adjustment of the disturbed conditions of cerebral growth and expansion and cranial equilibrium, that is, to indicate the existence of a biological or physical mechanism for coordinating the size of portions of the craniofacial structure in response to external mechanical factors through the process of their growth. The contrast in the susceptibility to the effects of artificial cranial deformation between the cranial vault and the facial skeleton has already been pointed out by DROESSLER (1981) and other previous authors.

matrices on craniofacial measurements for the three deformed and one undeformed Indian males.[1)]

						Between-group			
				Contri-bution of	Total vari-	Factor loadings[2)]		Contri-bution of	Total vari-
X	XI	XII	XIII	13 PCs (%)	ance	PC I	II	2 PCs (%)	ance
.04	.11	−.05	.33*	91.4	.43	.75*	.09	100.0	.57
−.06	−.19	−.15	−.08	76.1	.47	−.73*	−.00	98.9	.53
−.02	.01	.11	−.35*	98.9	.93	.18	.20	96.9	.07
.29	−.22	−.28	.15	95.6	.90	.27	−.16	99.3	.10
.09	.25	.14	.17	82.2	.50	.69*	.15	99.8	.50
−.03	.16	.04	.00	96.3	.85	.33*	−.16	89.0	.15
−.18	−.11	.15	.11	94.0	.89	.22	.22	92.4	.11
.08	.06	−.26	−.07	99.1	.98	.08	.10	76.3	.02
.19	.08	.21	.08	98.4	.98	−.07	−.03	26.2	.02
.06	−.19	.03	.04	92.9	.98	−.11	.09	90.3	.02
−.14	.15	−.05	−.19	87.8	.88	.33*	−.10	100.0	.12
−.20	−.12	−.14	.09	88.1	.91	−.26	.15	93.4	.09
.21	.36*	−.01	−.03	96.9	.93	.24	.09	88.2	.07
.36*	−.22	.22	−.10	95.2	.82	.35*	−.22	96.6	.18
.15	−.02	.01	−.05	99.8	.90	−.02	.31*	99.2	.10
−.30*	.07	−.01	.06	90.6	.93	.17	−.20	93.6	.07
.11	.09	−.18	−.13	91.6	1.00	−.02	.05	93.2	.00
−.11	−.15	.27	.04	99.3	.94	.00	.02	0.4	.06
.55	.50	.45	.40	93.9	15.19	2.24	.42	94.9	2.81
3.6	3.3	2.9	2.6	93.9	100.0	80.0	15.0	94.9	100.0
85.1	88.3	91.3	93.9	93.9	100.0	80.0	94.9	94.9	100.0

Further consideration on previous investigations

MacCurdy (1923) considered that a smaller foramen magnum in the deformed skulls from Peru was associated with the reduced dimensions of the spinal canal at its uppermost portion by the excessive Aymara deformation. But Oetteking (1930) thought that the comparative shortness of the foramen magnum in deformed skulls would be difficult to prove as the result of cranial deformation. Since both Aymara and Koskimo deformations are the annular (or circular or conical) type of deformation (Oetteking, 1930; Droessler, 1981), the results of PCAs for the Koskimo deformation group in the present study may answer this question: Fig. 2 suggests that there is no strong association between the conical deformation and the foramen magnum length or breadth. For the anteroposterior types of cranial deformation such as the Chinook, however, it is difficult to draw the same inference (Fig. 2).

Observing twenty-eight minor variants in bifronto-occipitally deformed and undeformed skulls, Ossenberg (1970) found that, in the deformed skull, traits at the back of the vault and in the frontal region revealed a hypostotic effect and, in contrast,

Table 10. Principal component analyses of the within- and between-group covariance skull series of American

	Within-group					
	Factor loadings[2]					
	PC I	II	III	IV	V	VI
Cranial length	.21	.23	.07	.34*	−.09	.08
Cranial breadth	.18	−.19	.06	−.14	.19	.05
ba-b height	.39*	.51*	−.23	.21	.30	−.21
Frontal chord	.17	.60*	−.24	.40*	.07	.14
Parietal chord	.09	.12	−.06	.20	.31*	−.39*
Occipital chord	.20	.34*	−.08	.35*	−.14	.42*
Cranial base length	.63*	.15	−.12	−.17	−.02	.12
Foramen magnum length	.23	−.21	.66*	.27	−.26	.07
Foramen magnum width	.46*	−.27	.41*	.54*	.07	.11
Facial length	.68*	−.32*	−.39*	−.11	−.28	.15
Upper facial height	.66*	.25	.14	−.17	−.20	−.18
Bizygomatic breadth	.61*	−.30*	.14	−.08	.43*	.15
Orbital breadth (*mf-ek*)	.55*	.12	.34*	−.23	.38*	−.04
Orbital height	.44*	.31*	.29	−.23	−.01	−.06
Nasal breadth	.40*	−.35*	−.32*	−.05	.29	.37*
Nasal height	.54*	.40*	.19	−.37*	−.26	.04
Maxillo-alveolar length	.72*	−.18	−.39*	.05	−.24	−.18
Maxillo-alveolar breadth	.50*	−.43*	−.11	.32*	−.11	−.44*
Total variance	3.93	1.84	1.45	1.30	.99	.87
Total contribution (%)	27.2	12.7	10.1	9.0	6.8	6.0
Cumulative proportion (%)	27.2	40.0	50.1	59.0	65.8	71.9

[1] A total number of individuals for the four series is 82.
[2] Covariances between the original variables and the standardized principal components.
* Greater than 0.30 in absolute value.

those of the lateral vault, facial skeleton and cranial base pointed to a general hyperostotic effect. This regularly modified pattern of the minor variants in the deformed skull seems fairly consistent with the hypothesis of coordinating mechanism mentioned above. Concerning wormian bones, however, it should also be noted that the determinants of this minor variant remain in controversy. As stated previously, OETTEKING (1930) suggested the retardation of the obliteration of main sutures on the cranial vault and the tendency for the formation of wormian bones to increase in deformed skulls. However, EL-NAJJAR and DAWSON (1977), using the samples of Southwestern Pueblo Indian skulls, found no significant association between the presence of wormian bones in the lambdoidal suture and the artificial cranial deformation. But, right after this, GOTTLIEB (1978) also observed the deformed and undeformed crania of Southwest Indians and found that while there was no relationship between the presence of wormian bones in the lambdoid suture and the artificial cranial deformation, the upper half of the lambdoid suture was more convoluted in the deformed crania than in the undeformed. And she, taking account of the positive matrices on craniofacial measurements for the three deformed and one underformed Indian females.[1)]

					Between-group			
			Contri- bution of 9 PCs (%)	Total vari- ance	Factor loadings[2)]		Contri- bution of 2 PCs (%)	Total vari- ance
VII	VIII	IX			PC I	II		
−.09	.07	.17	61.5	.44	.74*	.09	98.6	.56
.16	−.17	−.35*	70.4	.44	−.75*	.02	99.5	.56
−.20	−.12	−.04	83.4	.83	.36*	−.19	95.0	.17
.15	−.21	−.20	87.7	.83	.32*	.26	99.5	.17
−.13	−.05	.21	80.3	.47	.65*	−.30	95.7	.53
.14	.35*	−.03	88.1	.70	.25	.49*	99.3	.30
−.46*	−.05	.02	83.2	.83	.36*	−.17	89.7	.17
−.24	−.18	−.04	85.0	.90	.00	−.27	76.5	.10
−.09	−.06	.04	81.0	.96	−.16	−.08	72.5	.04
−.16	.04	−.09	89.8	.97	.06	.04	17.4	.03
.10	.02	.02	75.5	.84	.30	.27	99.7	.16
.23	−.10	−.13	85.6	.91	−.25	.09	77.2	.09
−.20	.41*	−.06	92.2	.92	.08	.24	74.9	.08
.36*	.05	.01	72.8	.77	−.01	.47*	96.2	.23
.10	−.11	.39*	92.1	.86	.15	−.23	52.1	.14
.11	−.23	.22	90.5	.90	.09	.30	99.9	.10
−.04	.04	−.17	87.0	.94	.09	.03	16.3	.06
.30	.10	.09	90.3	.96	−.07	.13	52.3	.04
.78	.52	.51	84.4	14.45	2.17	1.07	91.2	3.55
5.4	3.6	3.5	84.4	100.0	61.1	30.1	91.2	100.0
77.3	80.9	84.4	84.4	100.0	61.1	91.2	91.2	100.0

association between the sutural complexity and the mean number of wormian bones, inferred that cranial deformation seemed to have a direct effect of increasing the mean number of lambdoidal wormian bones, given their presence. In any case, there seems no doubt that artificial cranial deformation causes some morphological changes in the region of the lambdoid suture.

SCHENDEL *et al.* (1980) found through the comparison between Hawaiian deformed and undeformed skulls that the Hawaiian occipital deformation produced larger upper facial height, smaller glabella to occiput distance and larger lower facial height. For these, they postulated that the growth vectors in the neurocranial functional matrix, including the cranial base, were secondarily redirected to the orofacial functional matrix by external forces to the neurocranium. At least concerning the upper facial height, their result is supported by the present study (Fig. 2), though the types of deformations are different between Hawaii and the North Pacific coast. Their postulation for the findings conforms with the above hypothesis of coordinating mechanism.

McNEILL and NEWTON (1965) examined angular measurements of the anteroposteriorly and circumferentially deformed crania as well as the undeformed crania of the Amerinds from the Northwest Pacific coast, and found that the cranial vault deformations caused cranial base alterations such as elevation of the lateral orbital roofs and of the lateral petrous crests of the temporal bones, restriction of normal downward rotation of the foramen magnum, and flattening of the cranial base (platybasia) as reflected in the angle nasion-sella-basion (*Na-S-Ba*). HANZEL (1977) also found the flattening of the cranial base angle (*Na-S-Ba*) and the shortening of the distance from the point *S* to the line *Na-Ba* in the Peruvian deformed skulls of the annular type through both the univariate comparisons of linear and angular measurements and the principal component analysis of the covariance matrix only on angular measurements based on the combined sample consisting of deformed and undeformed skulls. Recently, ANTON (1989) further confirmed the above findings similarly on the basis of Peruvian deformed and undeformed crania, that is, found that alternative forms of the cranial base angle (*Na-S-Ba* and the like) and the orbital angle (orbital roof to the plane of the clivus) increased in both anteroposteriorly and circumferentially deformed groups compared with the undeformed. Among them, the elevation of the orbital roofs seems consistent with the findings for upper facial height in the present study and SCHENDEL *et al.* (1980).

Finally, MIZOGUCHI (1991), using a sample of modern Japanese undeformed skulls, suggested the relatively strong connection of maximum cranial breadth with bizygomatic breadth. Also in the present study, this connection is discernible in the factor loadings of the non-general-size factors not only from the undeformed skull series but also from anteroposterior and conical deformation series (Tables 3 to 8). This implies that there is a factor controlling both cranial and facial breadths which is independent of the general size factor and of external stresses such as artificial deformations.

In summary, the present study and most of previous studies showed that some consisitent morphological changes were caused by artificial vault deformations both in metric and in nonmetric cranial characters. From these, it is probable that there is a mechanism for regularly coordinating the size and shape of portions of the skull in response to external mechanical factors.

Summary and Conclusions

Using the data of the linear measurements obtained by OETTEKING (1930) from American Indian deformed and undeformed skulls, the affections of artificial cranial vault deformations on various parts of the vault and face were examined by the principal component analysis (PCA). The comparisons of the factor loadings of the principal components (PCs) from the PCAs for individual deformed and undeformed skull series revealed that the artificial deformations of both anteroposterior and conical types caused the intra-group variations common to the frontal and occipital chords as

well as to cranial length independently of the general size factor for the skull. The PCA of the between-group covariance matrix for the deformed and undeformed samples showed that the artificial deformations of the two kinds caused the between-group variations common to cranial length, parietal chord and upper facial height in the same direction and, simultaneously, the between-group variation of cranial breadth in the reverse direction. These results of the multivariate analyses, together with some previous investigations on interrelationships between artificial vault deformations and metric and/or nonmetric cranial characters, support the hypothesis that there is a mechanism for regularly coordinating the size and shape of portions of the craniofacial structure in response to external mechanical factors through the process of the growth, as has been inferred by OETTEKING (1930) and others.

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