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A Preliminary Evaluation of the Relationship between Dental Structure and Occlusal Wear Planes by the Method of Canonical Correlation Analysis

By

Yuji Mizoguchi

Department of Anthropology, National Science Museum, Tokyo

Abstract A canonical correlation analysis of the two sets of angles within the maxillary first molar, one relating to the occlusal wear planes and the other to the dental structure excluding the occlusal wear planes, suggested a trend that the more vertical the long axes of the buccal roots were to the cross section at the neck, the more horizontal the occlusal wear planes of the buccal cusps were.

It seems that each tooth has a structure which is successfully adapted to many factors including occlusal forces. Fujita (1973) states that mandibular molars move upward lingually during mastication, namely, the buccal cusps of the mandibular molars slide on the lingual surfaces of the buccal cusps of the maxillary molars and then strike the lingual cusps, when the direction of this movement coincides with that of longitudinal axes of the mandibular molars, and the maxillary molars resist the occlusal force in this direction with their powerful lingual roots. Osborn (1982) also states that the long axes of the molars or their roots are angled to the vertical in such a way as to resist tilting forces caused by the power stroke during mastication. On the other hand, Kovacs (1979) observed that there was a direct relation between the root surfaces and the strain applied to the tooth crowns by occlusal forces, *i.e.*, a broader root surface was correspondent to a broader occlusal surface. Smith (1984) illustrated that an oblique wear plane was expected to develop on the molar crown from near or actual tooth-to-tooth contact in chewing because the maxillary lingual and the mandibular buccal cusps received wear on both faces of cusp slopes while the remaining cusps wore on one face. In several species of primates including man, according to Molnar and Ward (1977), the enamel on the lingual cusps of the maxillary molars and on the buccal cusps of the mandibular molars is significantly thicker, and this distribution of thickened enamel is corresponding to the distribution of wear patterns. These observations and statements all suggest that the structure of tooth crown and roots as well as the position and inclination of a tooth within the alveolar process are closely associated with the function of a complex of jaws and teeth.

Occlusal wear planes can be considered as a result of the experiments done by the 'nature' on the relationship of dental morphology and its function. If various factors randomly influence the development of wear, it is expected that there may be no as-

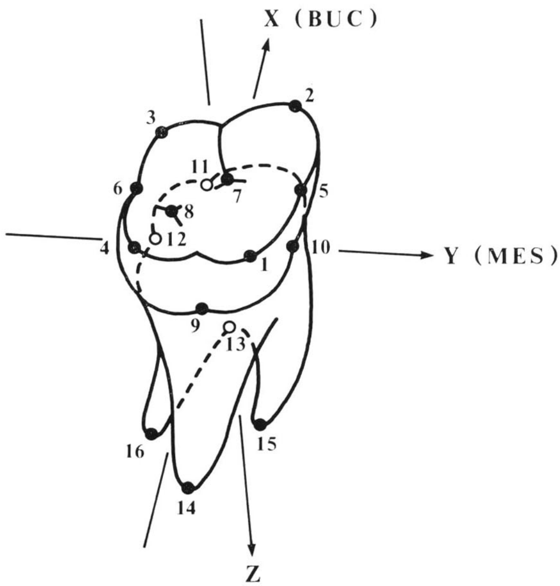

Fig. 1. Landmarks on the surface of the worn maxillary molar. See text for the definitions of the landmarks designated by the numerals 1 to 16.

sociations between the wear planes and dental structure, between the wear planes and jaw structure, between the wear planes and type/quantity of food, *etc.* This short paper is an attempt to find out some associations between dental structure and wear planes through a statistical analysis of the angles defined within the maxillary first molar.

Materials

Fifty isolated teeth from a human skeletal sample of the medieval period, about 650 years ago, were measured by the present author. This sample was excavated at the Gokurakuji site, Kamakura-shi, Kanagawa, in 1959 by Emeritus Professors Hisashi SUZUKI and Tsugio MIKAMI of the University of Tokyo, and consists of about 600 individuals. The 50 teeth, *i.e.*, 25 worn teeth and 25 unworn or little-worn teeth as a control, were extracted at random from several hundred isolated teeth which had in advance been identified as the right maxillary first molar regardless of sex by the present author. The worn teeth selected had almost the same stage of occlusal surface wear, *i.e.*, the grade '2' of BROCA's classification system (MARTIN und SALLER, 1957). Incidentally, the percentage of correct identification for the maxillary first molar has been reported to be 93.6% on the average of seven observer's results by FUJITA *et al.* (1960).

Table 1. Intraobserver error variances of the angles within the worn and unworn maxillary first molars based on the data obtained by the double determination method.

Angle between X–Y Plane and Segment:	Worn teeth: Variance[1)] Between classes (V_B) d.f.=24	Worn teeth: Variance[1)] Within classes (V_W) d.f.=25	Worn teeth: F-ratio	Unworn teeth: Variance [1)] Between classes (V_B) d.f.=24	Unworn teeth: Variance [1)] Within classes (V_W) d.f.=25	Unworn teeth: F-ratio
1–5	110.92	11.65	9.52**	59.65	6.88	8.67**
2–5	197.81	8.87	22.30**	118.88	13.15	9.04**
3–6	186.49	10.06	18.54**	90.68	15.33	5.92**
4–6	98.09	7.38	13.29**	54.28	9.37	5.79**
1–4	75.21	8.78	8.57**	28.09	5.46	5.14**
2–3	64.87	6.97	9.31**	29.68	13.44	2.21*
5–6	30.89	2.16	14.30**	19.46	1.03	18.89**
7–8	47.53	4.90	9.70**	43.31	7.81	5.55**
7–9	8.93	1.27	7.03**	13.03	1.70	7.66**
7–11	96.77	12.51	7.74**	93.12	16.33	5.70**
7–10	28.43	1.88	15.12**	26.76	3.25	8.23**
7–12	7.45	0.82	9.09**	13.80	1.16	11.90**
9–11	27.75	3.23	8.59**	28.19	3.71	7.60**
9–13	72.12	3.05	23.65**	38.12	2.05	18.60**
11–13	80.37	4.81	16.71**	28.97	2.73	10.61**
10–13	56.25	1.46	38.53**	33.81	0.69	49.00**
12–13	89.89	2.12	42.40**	45.23	2.04	22.17**
7–14	53.29	1.16	45.94**	15.85	1.49	10.64**
7–15	179.63	7.42	24.21**	94.99	6.88	13.81**
7–16	85.24	4.41	19.33**	55.14	3.85	14.32**
8–14	60.76	1.06	57.32**	20.12	1.77	11.37**
8–15	159.63	7.45	21.43**	81.25	6.34	12.82**
8–16	113.05	5.61	20.15**	75.50	4.66	16.20**

1) From the analysis of variance for one-way classification.
* $P<0.05$; ** $P<0.005$, by one-tailed F-test.

Methods

Three-dimensional measurements

First of all, 16 landmarks were defined on the surface of the maxillary molar as shown in Fig. 1. Points 1 to 4 are in the middle of the marginal arc of occlusal wear plane of each cusp, or on the apex of each cusp in the case of an unworn tooth. Points 5 and 6 are intermediate points between the buccal and lingual cusps on the marginal curve of the occlusal surface. Points 7 and 8 are intersections of the main occlusal surface grooves, and usually not affected by wear during the stage of wear adopted in the present study. Points 9 to 12 are intermediate points between the cusps on the

Table 2. Skewness and kurtosis for the angles within the worn and unworn maxillary first molars.

Angle between X–Y Plane and Segment:	Worn teeth (n=25)		Unworn teeth (n=25)	
	Skewness	Kurtosis	Skewness	Kurtosis
1–5	0.03	−1.04	0.29	0.16
2–5	−0.62	1.04	−0.22	1.14
3–6	0.50	0.13	−0.16	−0.28
4–6	−0.10	−1.15	−0.12	−0.16
1–4	0.47	−0.96	−0.51	−0.85
2–3	−0.62	−0.47	−1.53**	3.09**
5–6	0.59	−0.07	−0.54	0.08
7–8	0.63	−0.55	−0.36	−0.52
7–9	−0.50	2.31*	0.31	−0.48
7–11	0.78	−1.17	0.35	−0.18
7–10	0.22	−0.44	0.66	0.34
7–12	−0.08	−0.46	−0.13	0.76
9–11	0.07	−1.24	−0.19	−1.06
9–13	0.30	−0.62	−0.08	0.52
11–13	−0.42	0.35	0.10	−0.76
10–13	0.09	−0.40	−0.43	0.01
12–13	−0.50	−0.30	0.34	−0.21
7–14	−0.04	−0.22	−0.34	−0.42
7–15	0.79	−0.67	0.27	−0.32
7–16	0.50	−1.21	0.32	0.35
8–14	0.09	0.03	0.02	−0.32
8–15	0.69	−0.63	0.49	−0.02
8–16	0.54	−1.37	0.24	−0.02

* $P<0.05$; ** $P<0.001$.

cervical margin. Point 13 is the middle or meeting of the three roots. And Points 14 to 16 are apices of the roots.

The distances between three points on the cervical margin, Points 9, 10 and 12, were measured with a sliding caliper with an accuracy of 0.05 mm. Then, the distances from each of the other points to the three points were measured in the same way. Based on these measurements, three-dimensional coordinates for the 16 landmarks were calculated as in the three-dimensional craniometry carried out by BENFER (1975) and MIZOGUCHI (1984).

In the present study, 23 angles were defined between 23 line segments and the X–Y plane which was determined by Points 9, 10 and 12 (*e.g.*, see Table 1). Of these angles, seven are relating only to the worn or unworn occlusal surfaces, and the others to the structure which can not directly be affected by wear.

Statistical analysis

Intraobserver error variances of the angles defined within the maxillary first

Table 3. Comparisons of the angles in means and variances between the worn and unworn maxillary first molars.

Angle between X–Y Plane and Segment:	Worn teeth (n=25)		Unworn teeth (n=25)		Difference	
	Mean	Var.	Mean	Var.	t-value[1)]	F-ratio[2)]
1–5	−9.80	55.46	−22.54	29.82	6.90***	1.86
2–5	−32.86	98.91	−29.12	59.44	−1.48	1.66
3–6	−16.95	93.24	−20.87	45.34	1.66	2.06
4–6	−3.37	49.04	−18.45	27.14	8.64***	1.81
1–4	−7.21	37.61	−3.28	14.04	−2.74**	2.68*
2–3	−1.82	32.43	−0.67	14.84	−0.83	2.19
5–6	8.20	15.45	4.36	9.73	3.82***	1.59
7–8	10.81	23.76	12.67	21.66	−1.38	1.10
7–9	−34.95	4.47	−35.30	6.52	0.53	1.46
7–11	−32.58	48.39	−35.58	46.56	1.54	1.04
7–10	−52.42	14.21	−54.64	13.38	2.11*	1.06
7–12	−42.21	3.72	−41.64	6.90	−0.87	1.85
8–11	5.60	13.87	3.63	14.10	1.86	1.02
9–13	−45.62	36.06	−42.60	19.06	−2.03*	1.89
11–13	−45.65	40.19	−41.43	14.49	−2.85**	2.77*
10–13	−47.17	28.13	−43.67	16.91	−2.61**	1.66
12–13	−55.87	44.94	−53.49	22.61	−1.45	1.99
7–14	−65.45	26.64	−64.33	7.93	−0.96	3.36**
7–15	−60.62	89.82	−64.05	47.49	1.46	1.89
7–16	−55.24	42.62	−57.12	27.57	1.12	1.55
8–14	−71.45	30.38	−70.73	10.06	−0.57	3.02**
8–15	−57.11	79.82	−60.81	40.63	1.68	1.97
8–16	−57.75	56.53	−60.05	37.75	1.18	1.50

[1)] The differences in means of the first seven angles, *i.e.*, from '1–5' to '5–6,' were tested by COCHRAN's approximate significance test for the difference between two means with different variances (SNEDECOR and COCHRAN, 1967). The differences for the others were examined using STUDENT's t-test.

[2)] Two-tailed F-test.

* $P<0.05$; ** $P<0.01$; *** $P<0.001$.

molar were confirmed by the analysis of variance for one-way classification (KEMPTHORNE, 1969) based on the data of repeated measurements of all the subjects.

In order to examine the relationship between the variables on occlusal wear planes and those on the structure excluding the occlusal surface, the canonical correlation analysis (ANDERSON, 1958; ASANO, 1971; OKUNO *et al.*, 1971, 1976) was used.

Methods of calculation

All the calculations for statistical analysis were executed with the HITAC M-280H System of the Computer Centre, University of Tokyo. Basic statistics such as means, variances, skewness and kurtosis were calculated by the use of the BSFMD program.

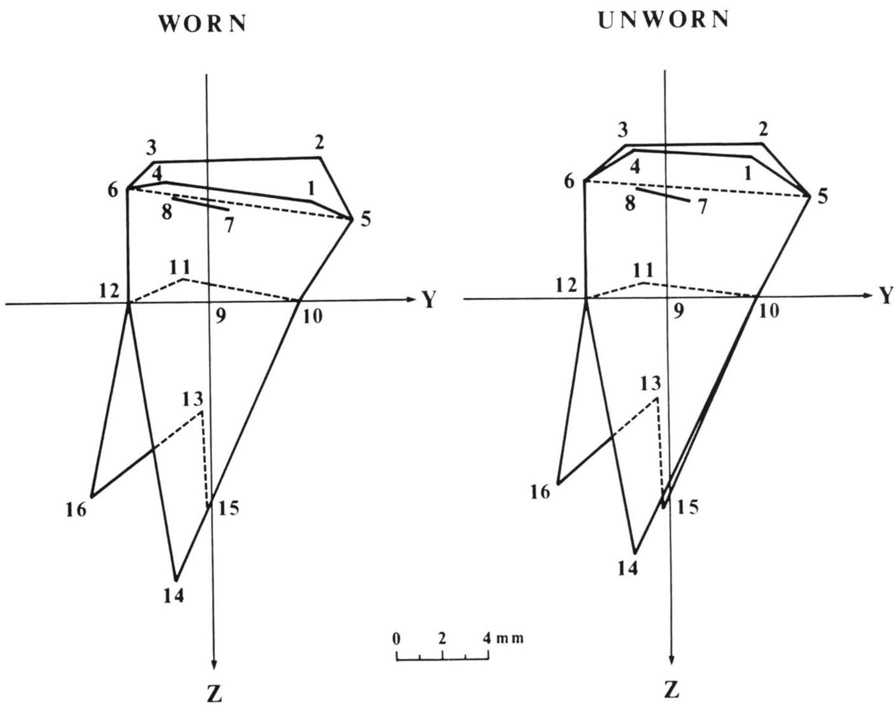

Fig. 2. Lingual view of the worn and unworn maxillary first molars from the Gokurakuji site, Kanagawa, based on the mean values of the three-dimensional coordinates.

The analysis of variance and the canonical correlation analysis were performed using the programs MIVCRL and CNCRSS, respectively. All the programs used here were written in FORTRAN by the present author.

Results

The intraobserver variances of the 23 angles within the maxillary first molar were tested through the analysis of variance based on the data of double measurements of the same subjects (Table 1). From these tests, it was found out that most of the percent error variances ranged between 5% and 30%, which could be obtained using the formula, $100V_W/(V_W+(V_B-V_W)/2)$. In the following analyses, an average of the double measurements was used as a value representing the relevant individual to minimize serious effect of the measurement errors.

In this study, sexing of the teeth was not attempted. In addition, there may be a few cases of misidentification of the position of the molars within the jaw. However, if the data collected here do not show extremely diverged variation, it seems not so problematic to use them for the purpose of this study. Although the sample size is not very large, the skewness and kurtosis for these data show that the distributions of most

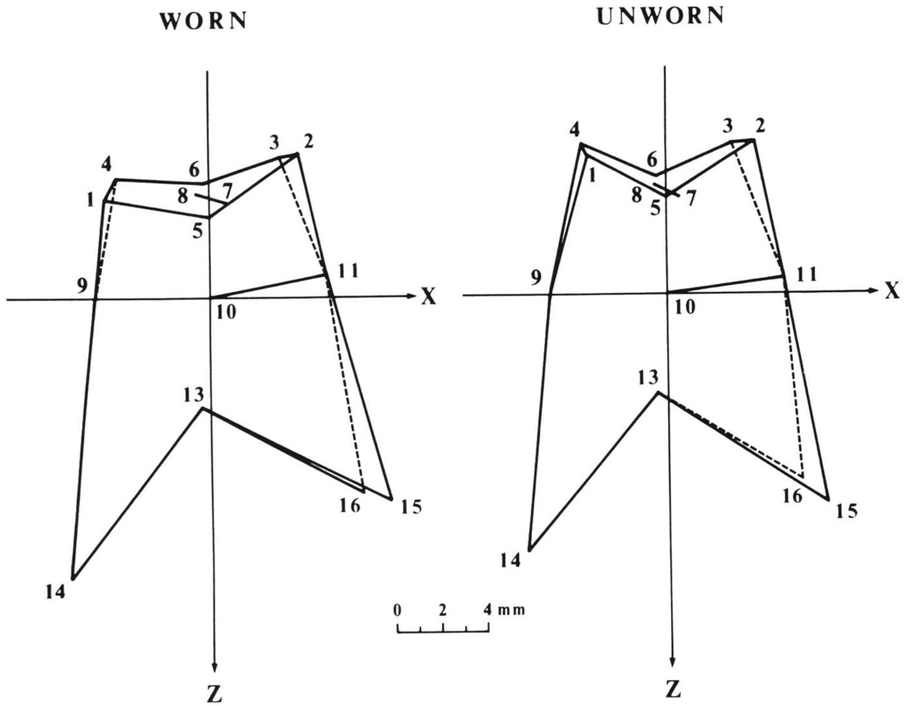

Fig. 3. Mesial view of the worn and unworn maxillary first molars from the Gokurakuji site, Kanagawa, based on the mean values of the three-dimensional coordinates.

variables are not significantly different from normal ones (Table 2).

The means and variances of the 23 angles and their differences between the worn and unworn teeth are shown in Table 3. The comparisons of the worn and unworn occlusal surfaces suggested that there were considerable differences between them, especially in means, as was expected. This is definitely illustrated in Figs. 2 and 3. The differences of the measurements relating to Point 13 between the worn and unworn tooth groups (Table 3) may be caused by the fact that a taurodont-like tooth was present in the worn tooth group, whereas the differences on Point 14 (Table 3) appear to be associated with incomplete maturity of the roots of some teeth in the unworn tooth group.

The results of canonical correlation analyses are shown in Table 4 and Fig. 4 for the worn teeth and in Table 5 and Fig. 5 for the unworn teeth. In both analyses of the worn and unworn tooth groups, only the first canonical correlation coefficient was statistically significant. However, the patterns in contribution of the first canonical variate to the original variables were considerably different between the worn and unworn tooth groups. The results from the worn maxillary first molars clearly showed that there was a tendency for the occlusal wear planes of the buccal cusps, especially

Table 4. Correlations between the canonical variates and original variables in the canonical correlation analysis of the angles relating to occlusal wear planes and to the other structure within the worn maxillary first molar.

Wear planes			The other structure		
Angle between X–Y Plane and Segment:	Canonical variate		Angle between X–Y Plane and Segment:	Canonical variate	
	u_1	u_2		v_1	v_2
1–5	.2903	−.3815	7–8	−.2514	.2289
2–5	.7854	.3893	7–9	−.1459	.3821
3–6	−.4055	.4693	7–11	−.7705	.1346
4–6	.2567	.0079	7–10	−.3029	.0857
1–4	.2102	−.2594	7–12	.1282	.2616
2–3	.6946	.2879	9–11	−.7932	.1046
5–6	−.3866	.4205	9–13	.0265	−.4894
Total contribution (%)	22.96	12.06	11–13	.1602	−.1941
			10–13	−.1303	−.1058
			12–13	−.0650	−.5542
			7–14	−.0897	.3042
			7–15	−.6325	−.1769
			7–16	−.5971	−.1202
			8–14	−.1069	.2045
			8–15	−.6438	−.2095
			8–16	−.6425	−.1327
			Total contribution (%)	19.16	7.13

Canonical correlation between u_1 and v_1: 0.9953 ($P=0.004$)
Canonical correlation between u_2 and v_2: 0.9498 ($P=0.262$)[1)]

[1)] The canonical correlations of the second to the seventh pair of canonical variates were found not to be significantly different from zero at the 5% level by Bartlett's method using Wilks' Λ (Asano, 1971; Rao, 1952).

paracone, to be more horizontal (Angles 2–5 and 2–3 in Fig. 4) as the long axes of the two buccal roots were more perpendicular to the cross section at the neck (Angles 7–15, 7–16, 8–15 and 8–16 in Fig. 4) and as the cervical margin on the buccal side moved toward the roots (Angles 7–11 and 9–11 in Fig. 4). This tendency is schematically illustrated in Fig. 6. On the other hand, the results from the unworn maxillary first molars showed that a factor controlling the buccolingual inclination of the occlusal surface of the protocone (Angle 1–5 in Fig. 5) and the mesiodistal inclination of the whole crown (Angles 5–6 and 1–4 in Fig. 5) was highly correlated to a complex of all the angles which were within the structure excluding occlusal surfaces and each subtly contributed to the complex.

Discussion

In the present study, some strong mutual associations were recognized between

Table 5. Correlations between the canonical variates and original variables in the canonical correlation analysis of the angles relating to occlusal surface and to the other structure within the unworn maxillary first molar.

Occlusal surface			The other structure		
Angle between X–Y Plane and Segment:	Canonical variate u_1	Canonical variate u_2	Angle between X–Y Plane and Segment:	Canonical variate v_1	Canonical variate v_2
1–5	.7005	.4226	7–8	−.2188	.3721
2–5	.4041	.5710	7–9	.1377	−.1214
3–6	−.3497	−.2551	7–11	−.2806	−.6145
4–6	.0621	.6606	7–10	.2462	−.3241
1–4	.4692	.2287	7–12	.2880	.2809
2–3	−.0482	.6910	9–11	−.3892	−.6891
5–6	−.9104	−.1072	9–13	−.2062	−.2867
Total contribution (%)	26.16	22.10	11–13	−.3557	.2590
			10–13	−.4157	−.3438
			12–13	−.2248	−.0641
			7–14	−.3740	−.1869
			7–15	−.2369	−.7464
			7–16	−.3062	−.5800
			8–14	−.2899	−.2931
			8–15	−.1512	−.7729
			8–16	−.3238	−.6282
			Total contribution (%)	8.34	21.67

Canonical correlation between u_1 and v_1: 0.9998 ($P=0.000002$)
Canonical correlation between u_2 and v_2: 0.9746 ($P=0.251$)[1)]

[1)] The canonical correlations of the second to the seventh pair of canonical variates were found not to be significantly different from zero at the 5% level by BARTLETT's method using WILKS' Λ (ASANO, 1971; RAO, 1952).

the occlusal wear planes and the structure excluding the occlusal surface in the worn maxillary first molar. This intensively suggests that the occlusal wear planes never develop at random. Further, from this result and the fact that another interrelation between the occlusal surface and the other structure was detected in the unworn tooth group (Tables 4 and 5; Figs. 4 and 5), it may be inferred that the dental structure is formed in advance during the ontogenetic process in such a way as to resist the occlusal forces which are to be generated in the future. That is to say, a relation which did not exist during the unworn stage appeared as the occlusal wear progressed. This seems to imply that each tooth has a structure which can function in response to those changes of itself and its environment which are prearranged for the organism who has it. It may also be said, however, that, together with other factors, the dental structure also plays a role as a guide in developing occlusal wear planes and, therefore, the above interrelations were found. The former explanation is for the phylogenetic morphogene-

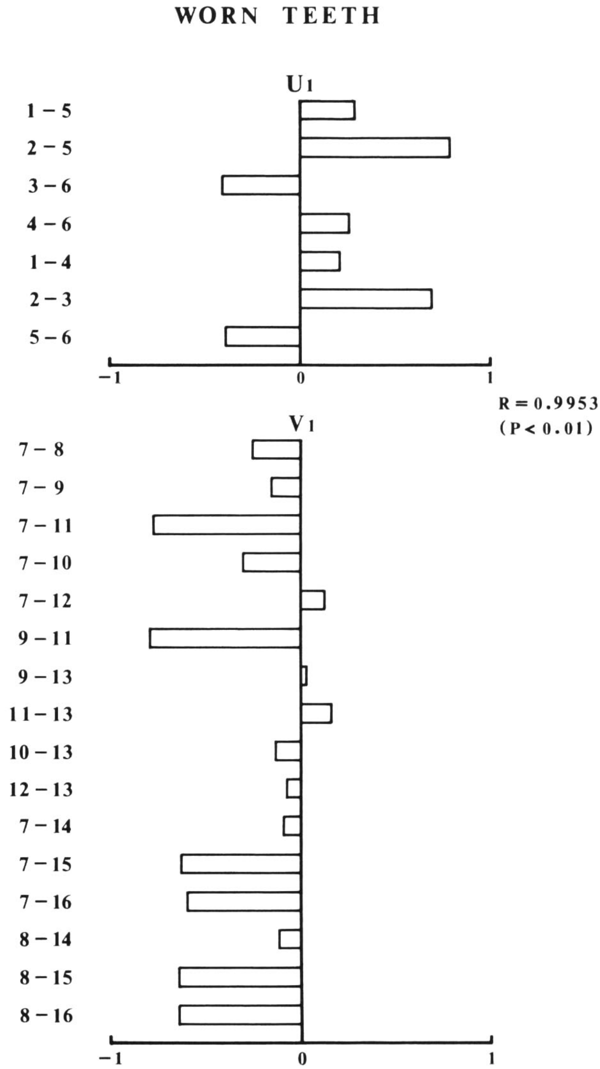

Fig. 4. Correlations between the first canonical variates and the original variables, *i.e.*, angles within the worn maxillary first molar. The numerals on the left side are labels of the landmarks illustrated in Fig. 1, a pair of the numerals designating an angle between the relevant line segment and the *X–Y* plane.

sis of the dental structure, while the latter is for the ontogenetic phenomenon in a broad sense.

The present study is preliminary work. Although the sexual dimorphism in the pattern and degree of dental wear has been reported (VAN REENEN, 1982; MOLNAR *et al.*, 1983), it was not taken into account here. Moreover, the roots of a tooth continue

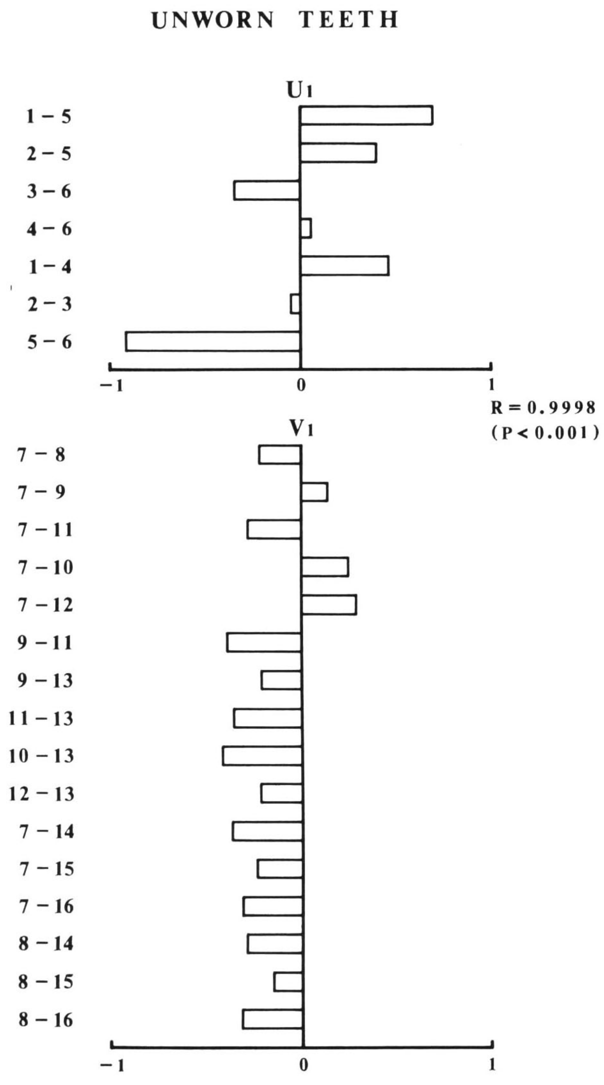

Fig. 5. Correlations between the first canonical variates and the original variables, *i.e.*, angles within the unworn maxillary first molar. The numerals on the left side are labels of the landmarks illustrated in Fig. 1, a pair of the numerals designating an angle between the relevant line segment and the *X–Y* plane.

to grow even after the time of occlusion and can change, especially at the apices, during the period of functioning (KOVACS, 1979). The interrelation between the occlusal wear planes and root inclination recognized in this study may partly be explained by presence of the long penetrating phase, if any, of the root growth and/or the resorption of root apices (KOVACS, 1979).

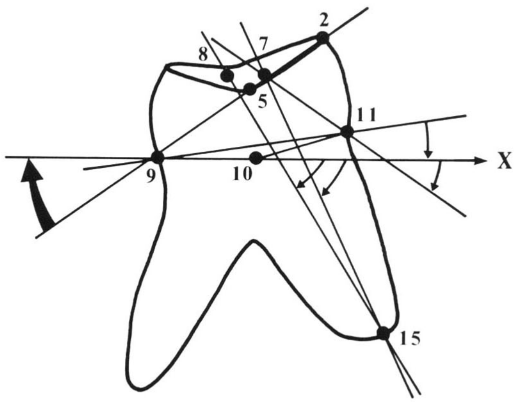

Fig. 6. Mesial view of the schematic worn maxillary first molar. The arrows show the directions of covariation between the angles.

BUTLER (1972) and HALL (1976) documented that the slope of occlusal wear planes in the molar teeth could considerably change as attritional level increased. TRATMAN (1950) noted that the roots of the maxillary first molars were shorter in the Mongoloid group than in the Indo-European group, and, further, that the roots of the former group showed less splay. These facts should also be taken into consideration for interpreting the relations between occlusal wear planes and dental structure. WARD and MOLNAR (1980) performed the experimental stress analysis of the human masticatory apparatus. TAKENAKA *et al.* (1985) developed a new system for three-dimensional measurements of fine occlusal wear facets. Such detailed and exact measurements and sophisticated biomechanical experiments will be foundations for understanding the interrelationship between morphology and function.

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