JOURNAL OF FORENSIC SCIENCES

J Forensic Sci, November 2014, Vol. 59, No. 6
doi: 10.1111/1556-4029.12540
Available online at: onlinelibrary.wiley.com

PAPER

ANTHROPOLOGY

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The Use of Tooth Crown Measurements in the Assessment of Ancestry

ABSTRACT: As the hardest tissue in the body, teeth have the potential to offer a wealth of biological information to the forensic anthropologist, which can include the assessment of ancestry. Using a large data set of dental measurements, the efficacy of mesiodistal and buccolingual tooth dimensions to discriminate between broad, geographically based groups is explored. A general pattern is identified: African populations have the largest teeth, Asians possess teeth of intermediate size, and Europeans have the smallest teeth. In a discriminant function analysis using crown measurements of all teeth (mandibular and maxillary and excluding the third molar), individuals were correctly classified in 71.3% of cases. When the sex of the individual is known, classification is improved up to 88.1% in females and 71.9% of males (cross-validated). Based on these results, we argue that dental metrics can be regularly employed as part of the development of the biological profile.

KEYWORDS: forensic science, forensic anthropology, dental metrics, ancestry, discriminant function, observer error

As the hardest tissue in the body, teeth are often well preserved and can provide the forensic anthropologist with a wealth of information. Aside from age estimation and for the purpose of identification, teeth have the potential to further aid in the biological profile to include the development of methods for the assessment of ancestry. Metric (1) and morphoscopic (2,3) methods of ancestry assessment have been explored in great depth, but only for cranial and postcranial remains. Dental morphology is gaining more visibility for the assessment of ancestry as methods for its application are being developed (4,5). This work stems from a rich history of anthropological studies that have identified broad population-level differences in dental morphology (6–11). Similar population differences exist in tooth crown dimensions. A general pattern of ancestral differences in tooth size has emerged in which Africans tend to have large teeth (particularly posterior teeth); Asians have intermediately sized teeth; and Europeans have small posterior teeth with larger anterior teeth (12). Hanihara and Ishida (13) describe a dental paradigm wherein Australians have the largest teeth, followed by Melanesians, Micronesians, sub-Saharan Africans, and Native Americans. East and Southeast Asians and Polynesians possess teeth intermediate in size, while Philippine Negritos, Jomon, Ainu, and Western Eurasians have the smallest teeth. Additionally, Schnutenhaus and Rösing (14), using a large data set of dental metrics, discovered that sample populations were largely separated by ancestry, in groups that they identified as "Europids, Melanesids, Negrids, and Mongolids" (p. 530).

Several studies have investigated the utility of dental metrics to differentiate populations and to classify individuals within those populations, all with varying levels of success (15–21). The primary purpose of this study is to present the utility of dental metrics in the assessment of ancestry using a large sample population.

Materials and Methods

Dental metrics were collected over a large span of time by one of the authors (TH) representing several regions of the world. Buccolingual and mesiodistal crown measurements were taken on all teeth from one side of the dental arcade, for a total of 32 metric variables per individual. Digital calipers calibrated to 0.01 mm were used to take measurements according to methods outlined by Moorrees (22) and Hillson (23). Several samples are from collections of known age and sex; however, when such information was not known, standard methods for the assessment of skeletal age and sex were employed (24). Skeletal samples were grouped by location of origin and regional group and were then assigned to one of three broad geographical regions—Africa, Asia, or Europe—based on the patterns of tooth size identified in previous studies (Table 1).

Data were subject to multiple statistical treatments to explore the accuracy of group classification and dental variation. These methods include summary statistics, one-way ANOVA, and discriminant function analysis (DFA). In the DFA, equal priors were used and the results are presented as the original and the cross-validated classifications. Cross-validated results create a discriminant function leaving one individual out and then classify that individual, thereby providing a more reliable function. Statistical analyses were conducted in SPSS 21.

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Received 3 June 2013; and in revised form 27 Nov. 2013; accepted 6 Oct. 2013.

TABLE 1—*Skeletal sample ancestral grouping and location.*

Broad Geographical Grouping	Regional group	Location	F	M	Total
Africa (n = 858)	East Africa	Kenya, Somalia, Tanzania, Uganda	42	304	346
	Sub-Saharan Africa	Cameroon, Congo, Ethiopia, Gabon, Gambia, Ghana Ashanti, Guinea, Ivory Coast, Lesotho, Malawi, Mozambique, Ruwanda, South Africa Bushman, South African Hottentot, South Africa Kaffir, South Africa Zulu, Zambia, Zimbabwe	33	282	315
	West Africa	Liberia, Niberia, Senegal, Sierra Leone	17	165	182
	Guyana	Guyana	0	8	8
	Jamaica	Jamaica	0	7	7
Asia (n = 3718)	Melanesia	Bismark, Fiji, New Britain, New Caldonia, New Hebrides, New Ireland, Papua New Guinea, Santa Cruz, Solomon, Torres Strait	277	618	895
	Micronesia	Caroline Islands, Caroline Ponape, Caroline, Gilbert Islands, Mariana Saipan, Mariana Tinian, Marshall Islands	25	73	98
	Native American	Alabama, Alaska, Arch Lake, Arizona, Arkansas, California, Colorado, Delaware, Florida, Georgia, Horn Shelter, Illinois, Kansas, Kentucky Indian Knoll, Kentucky, Louisiana, Maryland, Michigan, Mississippi, Missouri, Montana, Nebraska, Nevada, New Jersey, New Mexico, New York, North Dakota, Ohio, Oregon, Pennsylvania, South Dakota, Tennessee, Texas, Utah, Virginia, Washington, West Virginia, Wisconsin, Wyoming	294	433	727
	Polynesia	Chatham Islands Moriori, Cook Islands, Easter Islands, Gambier Islands, Hawaii, Marquesas, New Zealand Maori, Samoa, Society Islands, Tonga, Tuamotu Islands	252	718	970
	South East Asian	Bali, Borneo, Cambodia, Celebes, Java, Laos, Lesser Sunda, Maccassar, Malacca, Malay, Molucca, Myanmar, Negrito Phillipines, Negrito Semang, Nicobar Islands, Phillipines, Sulu, Sumatra, Sumbawa, Thailand, Timor, Vietnam	86	694	780
	East Asian	China, Japan, Korea	51	197	248
Europe (n = 1055)	Europe	Albania, Austria, Belgium, Bulgaria, Czecho, Denmark, Finland, France, Germany, Greece, Herzegovina, Holland, Hungary, Italy, Lapp, Norway, Poland, Portugal, Romania, Russia, Spain, Sweden, Switzerland, Yugoslavia	123	635	758
	Spitalfields	Spitalfields	102	195	297
Total			1302	4329	5631

Exploratory Analyses

Data were first explored to identify differences between geographical groups. A one-way ANOVA found all measurements to differ significantly between the three groups. The mean measurements for each sex and confidence intervals are provided in Tables 2 and 3. The general pattern of tooth size described in previous research was also found within this data set. African groups have the largest crown dimensions; Asians are intermediate in size; and Europeans have the smallest teeth. However, the anterior teeth of Asians and Africans are very similar in size. In several measurements, Asian teeth are slightly larger than African teeth. These measurements include the mesiodistal dimensions of the mandibular and maxillary second incisors, and the maxillary canine; and the buccolingual dimensions of the mandibular first and second incisors, and the maxillary first molar. Differences in these measurements between the African and Asian populations were explored in a one-way ANOVA. There were no statistically significant differences found in these measurements, indicating that these dimensions are essentially the same in these two groups. A pooled male/female data set was used for these analyses; however, similar results were obtained when the data were separated by sex.

Dental sexual dimorphism was also explored. In a one-way ANOVA, each metric variable was significantly different between the sexes ($p < 0.05$) except for the mesiodistal dimensions of the upper second incisor ($p = 0.086$), the lower first incisor ($p = 0.730$), and the lower second incisor ($p = 0.814$). A DFA using all 32 metric variables accurately classified sex in nearly 70% of cross-validated grouped cases.

Observer Error

To test replicability, and therefore the utility of dental metrics, a small observer error study was undertaken. Mesiodistal and buccolingual crown measurements were collected from the left dental arcade of five sets of dentition. Data were collected by two observers, one with extensive experience in the mensuration of teeth (MP) and one with less training (AH). The same set of Mitutoyo digital calipers calibrated to 0.01 mm was used by each observer. Error was divided by measurement type (mesiodistal, buccolingual) and location (maxillary, mandibular, anterior, posterior).

Interobserver measurement error was low in all areas; however, crown measurements of the maxillary posterior teeth showed the highest differences between observers (Table 4). This error fluctuated randomly in the buccolingual plane, as evidenced by the mean difference; however, the mesiodistal measurement had a large positive difference and standard deviation. This is likely a result of the inconsistent shape of the maxillary molars in the mesiodistal plane. The mesial and distal margins of these teeth have a tendency to angle mesially toward the cheek, which can make proper orientation and landmark identification difficult.

Dental measurements were also taken on three skulls by one observer (MP) on two occasions separated by a span of 3 months. Error was highest for mesiodistal measurements of maxillary posterior and anterior teeth (Table 5). Standard deviations reported here were lower than those in the interobserver error. In general, measurement fluctuations were random, with the exception of mesiodistal measurements of the maxillary teeth where a positive difference was noted. The positive difference in measurements of maxillary anterior teeth is an interesting finding and may relate to the correct placement of the caliper arms in the interproximal space of teeth for an accurate measurement. Overall, error was low in all measurements discussed here, approximating those reported in other studies (25–29).

Results

Discriminant function was used to explore group classification accuracies. First, only the polar teeth were used, that is, the teeth

TABLE 2—*Mean measurements and confidence intervals of female tooth dimensions by ancestral group.*

	Africa				Asian				Europe			
	Mean	*N*	95% Confidence Interval		Mean	*N*	95% Confidence Interval		Mean	*N*	95% Confidence Interval	
UI1_MD	9.21	11	8.9379	9.4857	8.57	318	8.5132	8.6350	8.22	49	8.0805	8.3521
UI2_MD	7.26	17	6.9097	7.6009	7.17	391	7.1169	7.2311	6.49	66	6.3483	6.6253
UC_MD	7.89	48	7.7512	8.0375	7.89	509	7.8443	7.9257	7.34	91	7.2556	7.4282
UP3_MD	7.52	69	7.4254	7.6190	7.24	579	7.2035	7.2751	6.57	111	6.4887	6.6486
UP4_MD	7.11	68	7.0046	7.2230	6.92	568	6.8791	6.9568	6.44	118	6.3583	6.5206
UM1_MD	11.00	85	10.8554	11.1389	10.73	823	10.6848	10.7687	10.21	143	10.1013	10.3159
UM2_MD	10.39	84	10.2334	10.5502	10.07	757	10.0188	10.1154	9.41	146	9.3125	9.5092
UM3_MD	9.22	69	9.0354	9.3967	9.34	452	9.2642	9.4111	8.72	83	8.5810	8.8674
LI1_MD	5.50	16	5.3488	5.6599	5.50	296	5.4652	5.5427	5.12	58	5.0360	5.2106
LI2_MD	6.20	22	6.0205	6.3786	6.19	363	6.1481	6.2324	5.67	81	5.5860	5.7572
LC_MD	7.16	29	6.9737	7.3470	6.90	415	6.8545	6.9395	6.39	79	6.3034	6.4667
LP3_MD	7.43	42	7.2617	7.5917	7.08	488	7.0390	7.1154	6.47	91	6.3737	6.5634
LP4_MD	7.56	44	7.4148	7.7075	7.23	480	7.1816	7.2709	6.77	100	6.6672	6.8678
LM1_MD	11.74	47	11.6084	11.8789	11.49	587	11.4400	11.5391	10.73	88	10.5904	10.8682
LM2_MD	11.03	47	10.8256	11.2387	10.94	605	10.8769	10.9974	10.29	98	10.1566	10.4150
LM3_MD	10.91	43	10.6239	11.1877	10.79	424	10.7000	10.8862	10.26	66	10.0854	10.4437
UI1_BL	7.42	14	7.1535	7.6879	7.28	334	7.2249	7.3253	6.92	56	6.8028	7.0444
UI2_BL	6.67	24	6.4810	6.8515	6.62	395	6.5757	6.6660	6.25	72	6.1040	6.3999
UC_BL	8.46	48	8.3021	8.6138	8.23	506	8.1854	8.2754	7.79	90	7.6755	7.9043
UP3_BL	9.67	68	9.5502	9.7948	9.58	574	9.5330	9.6265	8.61	111	8.5092	8.7144
UP4-BL	9.63	68	9.4928	9.7705	9.37	560	9.3231	9.4194	8.78	119	8.6700	8.8916
UM1_BL	11.57	85	11.4579	11.6906	11.60	822	11.5549	11.6367	11.04	143	10.9428	11.1376
UM2_BL	11.77	84	11.6111	11.9236	11.50	752	11.4479	11.5484	10.92	146	10.8177	11.0292
UM3_BL	11.27	69	11.0789	11.4521	10.98	457	10.9017	11.0537	10.41	83	10.2407	10.5803
LI1_BL	5.55	17	5.3920	5.7009	5.80	315	5.7521	5.8409	5.63	67	5.5411	5.7243
LI2_BL	6.10	23	5.9357	6.2556	6.21	378	6.1731	6.2550	6.02	84	5.9422	6.1071
LC_BL	7.55	29	7.3523	7.7497	7.50	423	7.4546	7.5500	7.13	87	7.0199	7.2486
LP3_BL	8.22	42	8.0794	8.3702	8.08	484	8.0286	8.1271	7.30	91	7.1818	7.4281
LP4_BL	8.52	44	8.3364	8.7109	8.39	475	8.3411	8.4379	7.90	97	7.7959	8.0082
LM1_BL	10.72	47	10.5659	10.8707	10.73	592	10.6809	10.7705	10.11	93	10.0109	10.2007
LM2_BL	10.42	47	10.2418	10.5918	10.32	600	10.2695	10.3692	9.72	98	9.6101	9.8356
LM3_BL	10.16	42	9.9571	10.3581	10.14	425	10.0683	10.2087	9.55	64	9.3845	9.7186

U, upper; L, lower; I, incisor; C, canine; P, premolar; M, molar; BL, buccolingual; MD, mesiodistal.

that are more stable in each tooth class and show higher heritabilities (30,31). Additionally, stepwise discriminant functions were conducted to identify those variables that best explain the variation in the sample. However, it was found that models consistently performed better when all teeth were used (not just the polar teeth or selected variables) and when the third molars were excluded, which were too variable and often missing. Removing the third molars resulted in 28 total measurements, down from the 32 described above. The initial data set ($n > 5600$) had a considerable amount of missing data that was found to be random throughout the dentition. We initially attempted various treatments to deal with missing data, including using the mean to replace the missing value and data imputation; all of these methods resulted in poorer model performance, and the effort was abandoned. Instead, those cases with missing data were removed, leaving only those individuals with all 28 measurements ($n = 508$; Table 6). This data set proved to be the most effective at distinguishing between ancestral groups and was therefore preferred for this analysis.

Ancestry Estimation

Data were first coded by regional group (indicated in Table 4 as "region") and evaluated as a method of ancestry estimation using DFA. This model correctly classified approximately 50% of the cross-validated cases into the 11 different groups. Next, data were coded by broad geographical location (Africa, Asia, and Europe) and reanalyzed in a DFA, which correctly classified 71.3% of cross-validated cases (Table 7). From these results, it was clear that the sample from Africa was problematic, with <50% of this sample classifying correctly in the cross-validated results. When these individuals were removed, and only samples from Asia and Europe were considered, classification results improved, nearing ninety percent correct classification (cross-validated; Table 8). Finally, the Asian and African samples were pooled since the summary statistics for these groups demonstrated correspondence in their tooth dimensions. Model performance was similar for this DFA, correctly classifying 84.6% of cross-validated cases (Table 9).

From the summary statistics and exploratory analyses, there were clear sex differences in dental dimensions. Therefore, additional analyses were performed to account for these differences. First, a DFA was used to classify individuals into one of six groups (either male or female, originating from Africa, Asia, or Europe). This model correctly classified 52.6% of cross-validated cases (Table 10). In this analysis, misclassification was common between African and Asian males and females. A plot of the group centroids using the first two functions illustrates these classification difficulties (Fig. 1), as there is a clear cluster of African males and females with Asian males. As sex differences within and between populations were leading to misclassifications, the data were further divided by males and females and then classified into the three geographical groups. These were by far the best classification models. When looking only at females,

TABLE 3—*Mean measurements and confidence intervals of male tooth dimensions by ancestral group.*

	Africa				Asian				Europe			
	Mean	*N*	95% Confidence Interval		Mean	*N*	95% Confidence Interval		Mean	*N*	95% Confidence Interval	
UI1_MD	8.98	95	8.8643	9.0934	8.72	725	8.6731	8.7582	8.43	172	8.3560	8.5065
UI2_MD	7.20	142	7.1131	7.2944	7.25	862	7.2089	7.2950	6.61	195	6.5370	6.6795
UC_MD	8.00	305	7.9491	8.0596	8.09	1248	8.0644	8.1200	7.61	314	7.5601	7.6600
UP3_MD	7.54	477	7.5009	7.5849	7.40	1607	7.3733	7.4184	6.76	428	6.7173	6.7978
UP4_MD	7.17	464	7.1237	7.2133	7.03	1599	7.0022	7.0512	6.55	445	6.5069	6.5844
UM1_MD	11.14	583	11.0901	11.1870	10.91	2182	10.8858	10.9378	10.49	527	10.4483	10.5384
UM2_MD	10.58	579	10.5150	10.6376	10.29	2015	10.2563	10.3175	9.77	559	9.7252	9.8246
UM3_MD	9.51	454	9.4359	9.5836	9.36	1257	9.3146	9.4091	9.00	329	8.9195	9.0744
LI1_MD	5.51	92	5.4345	5.5787	5.49	636	5.4608	5.5156	5.22	180	5.1754	5.2621
LI2_MD	6.15	145	6.0807	6.2135	6.16	798	6.1340	6.1936	5.83	234	5.7806	5.8746
LC_MD	7.31	225	7.2470	7.3766	7.16	997	7.1317	7.1907	6.69	286	6.6384	6.7425
LP3_MD	7.51	318	7.4540	7.5674	7.25	1242	7.2181	7.2722	6.72	338	6.6747	6.7725
LP4_MD	7.54	299	7.4775	7.6096	7.34	1238	7.3091	7.3692	6.92	338	6.8739	6.9722
LM1_MD	11.79	389	11.7305	11.8495	11.71	1530	11.6773	11.7397	11.09	362	11.0306	11.1474
LM2_MD	11.33	403	11.2614	11.4083	11.19	1528	11.1483	11.2285	10.70	408	10.6355	10.7699
LM3_MD	11.25	364	11.1520	11.3394	11.21	1190	11.1563	11.2634	10.69	309	10.5927	10.7865
UI1_BL	7.49	115	7.3981	7.5810	7.41	813	7.3730	7.4411	7.20	195	7.1365	7.2699
UI2_BL	6.84	170	6.7608	6.9236	6.74	927	6.7028	6.7706	6.46	217	6.3899	6.5295
UC_BL	8.69	319	8.6255	8.7579	8.56	1278	8.5259	8.5920	8.34	323	8.2797	8.4068
UP3_BL	9.85	473	9.7923	9.9019	9.82	1603	9.7892	9.8475	8.92	427	8.8631	8.9754
UP4-BL	9.78	467	9.7197	9.8362	9.65	1596	9.6208	9.6837	9.12	451	9.0627	9.1722
UM1_BL	11.77	593	11.7261	11.8239	11.87	2206	11.8433	11.8953	11.42	531	11.3728	11.4714
UM2_BL	12.04	588	11.9797	12.1083	11.92	2018	11.8893	11.9540	11.50	565	11.4444	11.5646
UM3_BL	11.73	466	11.6468	11.8122	11.39	1252	11.3402	11.4377	11.04	328	10.9352	11.1383
LI1_BL	5.83	103	5.7433	5.9134	5.93	704	5.9009	5.9606	5.85	205	5.7967	5.9064
LI2_BL	6.31	159	6.2422	6.3709	6.33	845	6.3018	6.3568	6.21	256	6.1564	6.2611
LC_BL	7.98	238	7.9067	8.0562	7.92	1037	7.8870	7.9595	7.75	301	7.6837	7.8168
LP3_BL	8.45	317	8.3804	8.5161	8.32	1236	8.2891	8.3531	7.69	340	7.6360	7.7482
LP4_BL	8.68	301	8.6111	8.7577	8.60	1224	8.5705	8.6359	8.19	340	8.1359	8.2535
LM1_BL	10.93	383	10.8716	10.9907	10.96	1527	10.9306	10.9880	10.44	380	10.3899	10.4905
LM2_BL	10.66	399	10.5931	10.7223	10.59	1518	10.5612	10.6250	10.12	409	10.0690	10.1790
LM3_BL	10.53	359	10.4564	10.6079	10.44	1186	10.4042	10.4849	9.91	310	9.8353	9.9928

U, upper; L, lower; I, incisor; C, canine; P, premolar; M, molar; BL, buccolingual; MD, mesiodistal.

TABLE 4—*Results of interobserver error test.*

	Posterior Teeth				Anterior Teeth			
	Mandible		Maxilla		Mandible		Maxilla	
	BL	MD	BL	MD	BL	MD	BL	MD
Mean difference	0.08	0.09	0.07	0.23	−0.07	0.07	−0.07	−0.08
Mean difference standard deviation	0.37	0.34	0.48	0.90	0.33	0.32	0.29	0.35
Absolute value of mean difference	0.28	0.24	0.32	0.57	0.23	0.22	0.22	0.23
Absolute value of mean difference standard deviation	0.25	0.24	0.36	0.73	0.24	0.24	0.20	0.27

BL, buccolingual; MD, mesiodistal.

TABLE 5—*Results of intraobserver error test.*

	Posterior Teeth				Anterior Teeth			
	Mandible		Maxilla		Mandible		Maxilla	
	BL	MD	BL	MD	BL	MD	BL	MD
Mean difference	−0.03	0.11	−0.08	0.22	0.17	0.02	0.01	0.23
Mean difference standard deviation	0.23	0.24	0.36	0.18	0.27	0.16	0.24	0.36
Absolute value of mean difference	0.16	0.21	0.27	0.24	0.23	0.13	0.19	0.31
Absolute value of mean difference standard deviation	0.15	0.14	0.24	0.14	0.21	0.08	0.13	0.29

BL, buccolingual; MD, mesiodistal.

TABLE 6—*Individuals with complete data sets.*

Broad Geographical Location	Region	F	M	Total
Africa (n = 31)	East Africa	1	16	17
	Sub-Saharan Africa	0	13	13
	West Africa	1	0	1
Asia (n = 432)	East Asian	1	54	55
	Melanesia	11	27	38
	Micronesia	1	10	11
	Nat Am	76	98	174
	Polynesia	53	56	109
	South East Asian	4	41	45
Europe (N = 45)	Spitalfields	3	7	10
	Europe	8	27	35
	Total	159	349	508

TABLE 7—*Classification results of discriminant function of individuals into three broad geographical groups (Africa, Asia, and Europe).*

			Predicted Group Membership		
			Africa	Asia	Europe
Original	Count	Africa	22	6	3
		Asia	72	329	31
		Europe	3	4	38
	%	Africa	71.0	19.4	9.7
		Asia	16.7	76.2	7.2
		Europe	6.7	8.9	84.4
Cross-validated	Count	Africa	15	11	5
		Asia	82	313	37
		Europe	4	7	34
	%	Africa	48.4	35.5	16.1
		Asia	19.0	72.5	8.6
		Europe	8.9	15.6	75.6

76.6% of original grouped cases correctly classified.
71.3% of cross-validated grouped cases correctly classified.

TABLE 8—*Classification results of discriminant function of individuals into two broad geographical groups (Asia and Europe).*

			Predicted Group Membership	
			Asia	Europe
Original	Count	Asia	387	45
		Europe	6	39
	%	Asia	89.6	10.4
		Europe	13.3	86.7
Cross-validated	Count	Asia	382	50
		Europe	10	35
	%	Asia	88.4	11.6
		Europe	22.2	77.8

89.3% of original grouped cases correctly classified.
87.4% of cross-validated grouped cases correctly classified.

TABLE 9—*Classification results of discriminant function of individuals into two groups (pooled Asian and African sample and Europe).*

			Predicted Group Membership	
			Pooled Africa and Asia	European
Original	Count	Pooled Africa and Asia	277	38
		European	4	31
	%	Pooled Africa and Asia	87.9	12.1
		European	11.4	88.6
Cross-validated	Count	Pooled Africa and Asia	270	45
		European	9	26
	%	Pooled Africa and Asia	85.7	14.3
		European	25.7	74.3

88.0% of original grouped cases correctly classified.
84.6% of cross-validated grouped cases correctly classified.

88.1% of cross-validated cases were correctly classified (Table 11). When only males were considered, 71.9% of cross-validated cases were correctly classified (Table 12).

Discriminant Function Equations

Data were separated by males and females and then a two-step analysis was created to classify individuals based on dental metrics. Discriminant function equations were created using 28 metric variables as these produced the most reliable models. In Table 13, equations are provided to distinguish African/Asian groups from European groups. Then a second set of equations is provided to discriminate between African and Asian groups (Table 14). Classification boundaries were defined as the mean of the function for each group and are provided with each equation. The population pyramids for the equations are provided in Fig. 2. Also provided as part of Tables 13 and 14 are the percentages of individuals correctly classified in each model and the level of significance. Caution should be employed in the application of Equation 2 for females (Table 14) as the Wilk's lambda level of significance is >0.05; this nonsignificant result is likely the result of sample size.

Discussion

The results of our analysis identify broad, geographically based differences in tooth size. However, due to small sample sizes, there is the potential for over fitting in some of these models. Results also indicate that there is significant sexual dimorphism that varies both within and between populations. There is the potential to misclassify individuals when sex is not known as there is some overlap in tooth size across sexes and ancestral groups, particularly between African females and Asian males. Therefore, models that account for sexual variation greatly improve classification accuracies. Ideally, a larger data set with more African individuals would help to resolve some of these sampling issues.

Based on these results, tooth size can be correlated to sex and population. In fact, studies have demonstrated that additive genetic effects account for 60–91% of observed dental metric variation (30,32–34). While sex clearly plays a role in tooth size, these genetically based population differences may relate to a variety of factors to include drift and selection. Hanihara (35) argued that population differences in dental size and morphology could be explained through a single origin hypothesis of anatomically modern humans. Africans show less derived teeth, whereas other populations show more specialized dental features and a general reduction in tooth size. Tooth size is likely related to the changing morphology of the dental crown through human evolution. Other researchers have argued that crown complexity is positively associated with crown size (36,37), and these same

TABLE 10—*Classification results of discriminant function into six groups: males and females from Asia, Africa, or Europe.*

			Predicted Group Membership					
			African—F	African—M	Asia—F	Asia—M	European—F	European—M
Original	Count	African—F	2	0	0	0	0	0
		African—M	0	20	3	4	1	1
		Asia—F	4	13	99	18	5	7
		Asia—M	9	34	66	158	4	15
		European—F	0	0	0	0	10	1
		European—M	0	3	0	3	3	25
	%	African—F	100.0	0	0	0	0	0
		African—M	0	69.0	10.3	13.8	3.4	3.4
		Asia—F	2.7	8.9	67.8	12.3	3.4	4.8
		Asia—M	3.1	11.9	23.1	55.2	1.4	5.2
		European—F	0	0	0	0	90.9	9.1
		European—M	0	8.8	0	8.8	8.8	73.5
Cross-validated	Count	African—F	0	0	0	2	0	0
		African—M	0	15	4	6	1	3
		Asia—F	6	15	85	23	7	10
		Asia—M	12	40	70	140	4	20
		European—F	0	0	0	0	8	3
		European—M	0	4	1	6	4	19
	%	African—F	0	0	0	100.0	0	0
		African—M	0	51.7	13.8	20.7	3.4	10.3
		Asia—F	4.1	10.3	58.2	15.8	4.8	6.8
		Asia—M	4.2	14.0	24.5	49.0	1.4	7.0
		European—F	0	0	0	0	72.7	27.3
		European—M	0	11.8	2.9	17.6	11.8	55.9

61.8% of original grouped cases correctly classified.
52.6% of cross-validated grouped cases correctly classified.

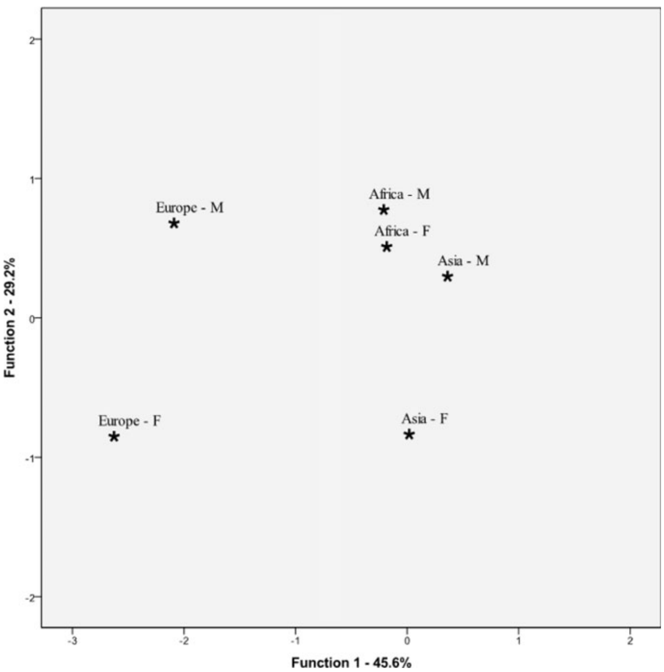

FIG. 1—*Plot of discriminant function analysis indicating centroids for the six groups based on sex and geographical region (M = male, F = female).*

TABLE 11—*Classification results of discriminant function of females only into three geographical groups.*

			Predicted Group Membership		
			Africa	Asia	Europe
Original	Count	Africa	2	0	0
		Asia	2	135	9
		Europe	0	0	11
	%	Africa	100.0	0	0
		Asia	1.4	92.5	6.2
		Europe	0	0	100.0
Cross-validated	Count	Africa	0	1	1
		Asia	4	131	11
		Europe	0	2	9
	%	Africa	0	50.0	50.0
		Asia	2.7	89.7	7.5
		Europe	0	18.2	81.8

93.1% of original grouped cases correctly classified.
88.1% of cross-validated grouped cases correctly classified.

patterns of crown complexity can be associated with these geographical groups.

There could also be underlying biological factors related to these population differences. Harris et al. (38) suggested that dental tissues in deciduous teeth are larger in Blacks than in Whites, which may account for size differences. Additionally, crown formation rates have been identified between American Blacks and Whites, with American Blacks reaching formation sooner than American Whites (39–41), which may have implications for overall tooth size as well.

Conclusions

As teeth are often well preserved, they can be of great utility in the development of the biological profile. Based on the results presented herein, dental metrics provide an additional tool for the assessment of ancestry. Not only are tooth dimensions generally quick and easy to record, they can be accurately taken by individuals with limited training.

TABLE 12—*Classification results of discriminant function of males only into three geographical groups.*

			Predicted Group Membership		
			Africa	Asia	Europe
Original	Count	Africa	22	5	2
		Asia	40	226	20
		Europe	4	4	26
	%	Africa	75.9	17.2	6.9
		Asia	14.0	79.0	7.0
		Europe	11.8	11.8	76.5
Cross-validated	Count	Africa	15	8	6
		Asia	43	216	27
		Europe	5	9	20
	%	Africa	51.7	27.6	20.7
		Asia	15.0	75.5	9.4
		Europe	14.7	26.5	58.8

78.5% of original grouped cases correctly classified.
71.9% of cross-validated grouped cases correctly classified.

Dental measurements have the potential to be analyzed in much the same way as cranial measurements. Data on tooth dimensions could be incorporated into computerized statistical programs, such as FORDISC (1), and provide cross-validated classification results for individuals within a forensic context. The creation of such a statistical package using these data would allow for the analyst to evaluate ancestry using only those measurements available; much the same way craniometrics are analyzed. Therefore, it would not be necessary for each tooth to be present, and analyses could proceed on limited sets of dentition. This type of analysis would be much preferred in a forensic setting where teeth are often missing.

We argue here for the inclusion of dental metrics as part of the biological profile and for the development of a larger sample database to improve the efficacy of this method. With the inclusion of more data on complete sets of dentition, it is plausible that the correct classification of individuals to ancestral groups using tooth dimensions could be greatly improved.

TABLE 13—*Discriminant function equations to distinguish between Africans/Asians and Europeans.*

Equation 1. Females													
UI1_MD	UI2_MD	UC_MD	UP3_MD	UP4_MD	UM1_MD	UM2_MD	LI1_MD	LI2_MD	LC_MD	LP3_MD	LP4_MD	LM1_MD	LM2_MD
−0.765	1.265	0.156	0.003	0.560	−0.316	−0.195	−0.155	0.920	−1.297	−0.155	−0.087	1.236	0.456
UI1_BL	UI2_BL	UC_BL	UP3_BL	UP4_BL	UM1_BL	UM2_BL	LI1_BL	LI2_BL	LC_BL	LP3_BL	LP4_BL	LM1_BL	LM2_BL
0.440	−0.855	−0.157	1.373	−0.322	0.996	−0.178	0.297	−0.316	−0.183	1.120	−0.844	−0.746	−0.564
Equation 1. Males													
UI1_MD	UI2_MD	UC_MD	UP3_MD	UP4_MD	UM1_MD	UM2_MD	LI1_MD	LI2_MD	LC_MD	LP3_MD	LP4_MD	LM1_MD	LM2_MD
−.330	.229	.542	−.204	.384	−.349	.118	.120	.049	.321	.111	.254	.597	−.002
UI1_BL	UI2_BL	UC_BL	UP3_BL	UP4-BL	UM1_BL	UM2_BL	LI1_BL	LI2_BL	LC_BL	LP3_BL	LP4_BL	LM1_BL	LM2_BL
.176	−.074	−.895	1.350	−.603	.060	−.480	−.226	.360	−.226	1.273	−1.080	.335	.158

U, upper; L, lower; I, incisor; C, canine; P, premolar; M, molar; BL, buccolingual; MD, mesiodistal.

Female: Constant = −17.870; Wilk's lambda significance = 0.000; 95.0% of original grouped cases correctly classified; 91.2% of cross-validated grouped cases correctly classified; Functions at group centroids: African/Asian = 0.240, European = −3.224; Results > −1.492 indicate African/Asian ancestry.

Male: Constant = −15.949; Wilk's lambda significance = 0.000; 90.5% of original grouped cases correctly classified; 86.2% of cross-validated grouped cases correctly classified; Functions at group centroids: African/Asian = 0.237, European = −2.194; Results > −0.979 indicate African/Asian ancestry.

TABLE 14—*Discriminant function equations to distinguish between Africans and Asians.*

Equation 2. Females													
UI1_MD	UI2_MD	UC_MD	UP3_MD	UP4_MD	UM1_MD	UM2_MD	LI1_MD	LI2_MD	LC_MD	LP3_MD	LP4_MD	LM1_MD	LM2_MD
.303	.531	.960	.216	−.203	1.124	.295	.451	−1.082	−2.210	1.013	−.096	−1.220	−.030
UI1_BL	UI2_BL	UC_BL	UP3_BL	UP4-BL	UM1_BL	UM2_BL	LI1_BL	LI2_BL	LC_BL	LP3_BL	LP4_BL	LM1_BL	LM2_BL
.206	.060	−.022	−.174	.192	1.033	−1.091	1.067	.782	−1.171	.886	−2.096	.414	.152
Equation 2. Males													
UI1_MD	UI2_MD	UC_MD	UP3_MD	UP4_MD	UM1_MD	UM2_MD	LI1_MD	LI2_MD	LC_MD	LP3_MD	LP4_MD	LM1_MD	LM2_MD
1.125	−.476	−1.184	.555	−.529	.577	.789	−.713	−.669	.510	.742	.173	−.640	.207
UI1_BL	UI2_BL	UC_BL	UP3_BL	UP4-BL	UM1_BL	UM2_BL	LI1_BL	LI2_BL	LC_BL	LP3_BL	LP4_BL	LM1_BL	LM2_BL
.098	.543	.515	−.696	.028	−.584	.012	−1.526	.472	.096	.519	.141	−.043	−.869

U, upper; L, lower; I, incisor; C, canine; P, premolar; M, molar; BL, buccolingual; MD, mesiodistal.

Females: Constant = −1.003; Wilk's lambda significance = 0.221; 98.6% of original grouped cases correctly classified; 95.3% of cross-validated grouped cases correctly classified; Functions at group centroids: African = −4.553, Asian = 0.062; Results > −2.246 indicate Asian ancestry.

Males: Constant = 5.322; Wilk's lambda significance = 0.000; 83.5% of original grouped cases correctly classified; 79.4% of cross-validated grouped cases correctly classified; Functions at group centroids: African = 1.745, Asian = −0.177; Results > 0.784 indicate African ancestry.

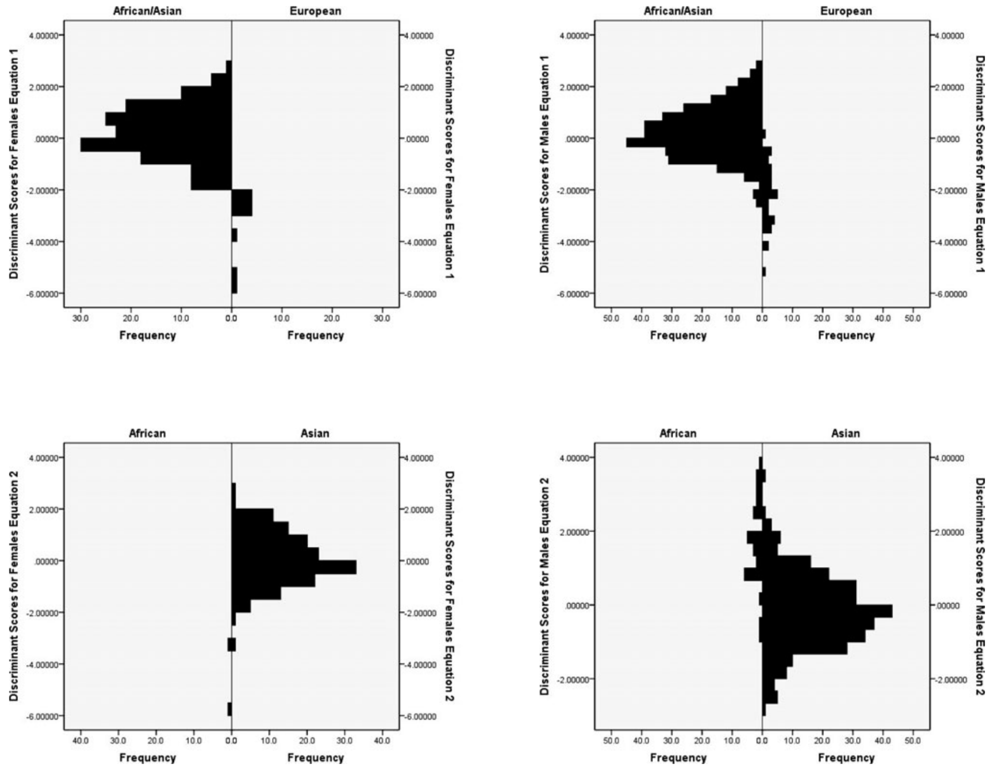

FIG. 2—*Population pyramids based on discriminant function equations.*

Acknowledgments

We thank Casey Philbin for assistance with data management, and Nicholas V. Passalacqua and two anonymous reviewers for comments on earlier drafts of this paper.

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