ORIGINAL ARTICLE AJO-DO

Preliminary biometric analysis of mesiodistal tooth dimensions in subjects with normal occlusion

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Introduction: The aims of this study were to confirm the efficacy of the Bolton index in a group of natural Class I white Italian patients with complete dentition, minimal crowding, and no previous orthodontic treatment, and to evaluate the mesiodistal tooth dimensions with multivariate cluster analysis. **Methods:** Tooth measurements were obtained from a sample of 56 patients with normal occlusion, with a normal Bolton index (22 men, 34 women; mean age, 27.8 years), without previous orthodontic treatment or prosthetic or Class II restorations. Maxillary and mandibular measurements were analyzed separately in the sexes. Clustering was performed using the partitioning around medoid algorithm and principal component analysis-based transformed data. Statistical analysis was conducted. **Results:** The multivariate analysis showed 3 distinct clusters of both maxillary and mandibular tooth measurements in the male and female subjects. Statistically significant differences were found between the sexes in terms of average tooth measurements, and there was significant proportionality between the maxillary and mandibular arch clusters. **Conclusion:** Although the Bolton index is useful for identifying dentodental discrepancies in most patients, cluster analysis enabled the mandibular and maxillary tooth dimensions of the male and female subjects to be divided into 3 general classes (clusters) and the precise location of the discrepancies to be pinpointed. (Am J Orthod Dentofacial Orthop 2016;150:105-15)

To assess the degree of crowding, the dentodental relationships between the maxillary and mandibular teeth, as well as the skeletal and dentobasal relationships, need to be determined with precision. It is therefore vital to consider the dimensions of the individual teeth before treatment with a view to quantifying and localizing any dental discrepancies[1-21] and planning the amount of stripping or restorative buildup required, all prerequisites for good occlusal interdigitation.[17]

The most common method of identifying and calculating the degree of dental discrepancy, and determining whether it is in the anterior or posterior sector, is the Bolton index.[8,9] In subjects with normal occlusion, Bolton reported an overall mean intermaxillary dentodental relationship from first molar to first molar of 91.3 ± 0.26, and an anterior relationship from canine to canine of 77.2 ± 0.22.[7] However, the Bolton index has certain limitations. First and foremost, the overall and anterior ratios have wide ranges (anterior ratio, 74.5-80.4; overall ratio, 87.5-94.8), implying an equally wide range of what is considered normal in an optimal occlusion.[11] Furthermore, the index cannot tell us the precise location of the discrepancy in a sector or quantify its severity.[11] It also cannot account for ethnic variations,[12-15] and because it relies on measurements made on plaster models, it is subject to imprecision.[18,22-24]

Nevertheless, many authors assert that the Bolton index can be correlated with the type of malocclusion. Nie and Lin,[10] for example, measured this parameter in 300 orthodontic patients, classified according to their malocclusion type (Class I, Class II, and Class III); they found that Class III patients tended to have higher Bolton index values than Class I patients, whereas Class II patients tended to be correlated with lower Bolton index values.[10] Hence, according to some authors, a Class III malocclusion is correlated with a relative excess in the mandibular dentition, whereas Class II involves a relative excess in the maxillary dentition. However, in their review of the literature on tooth size discrepancies,

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All authors have completed and submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest, and none were reported.
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Submitted, October 2014; revised and accepted, December 2015.
0889-5406/$36.00

http://dx.doi.org/10.1016/j.ajodo.2015.12.021

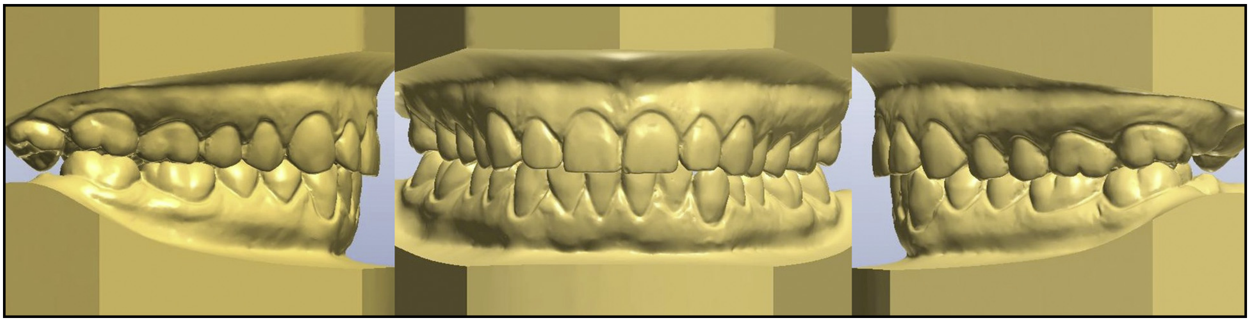

Fig 1. Plaster models were scanned with the 3D 3Shape R700 scanner.

Othman and Harradine[11] concluded that the standard deviations of the Bolton indexes are not an ideal guide for evaluating clinically significant discrepancies in tooth dimensions. They also stated that researchers should focus more on the degree of the discrepancy, rather than just the Bolton index alone.

Whatever the case, the job of measuring tooth dimensions and the Bolton index has been made considerably easier of late because of digital gauges and their dedicated software, and the measurement of dental discrepancies will gradually become routine in clinical practice. Hence, it is timely to analyze such dimensions using the latest technological and statistical analysis tools. In particular, we set out to use these tools for the following.

1. Verify the validity of the Bolton indexes in a sample of untreated naturally Class I white Italian subjects with complete dentition and minimal crowding.
2. Measure the mesiodistal diameters of the tooth crowns, analyze the data via multivariate cluster analysis (men, women, maxillary teeth, and mandibular teeth), and ultimately propose a method for the precise localization and quantification of the interarch discrepancy, thereby overcoming some limitations of the Bolton index.

MATERIAL AND METHODS

Tooth measurements were taken in a sample of 56 white Italian patients (22 men, 34 women; mean age, 27.8 years) with normal occlusion, selected according to the following criteria: Class I molar and canine relationships, complete dentition excluding the third molars, normal overjet and overbite (1-3 mm), minimal crowding (<1.5 mm, considering both arches), no previous orthodontic, prosthetic, or conservative treatment (no restorations according to Black's classification of cavities).

Plaster models of these 56 patients' dentitions were scanned with a 3-dimensional (3D) 3Shape R700 scanner (Great Lakes Orthodontics, Tonawanda, NY), and the mesiodistal diameters of each crown, from second molar to second molar, were measured with the 3Shape OrthoAnalyzer software (Fig 1). An example of the scanned 3D dental cast is available in Supplemental Material.

To obtain precise, reliable measurements, each tooth was measured as follows.

On a vestibular view of each tooth (Fig 2), the "2D cross-section" tool was used to section the digital rendering; the incisors were sectioned from the distal point of contact, keeping the plane parallel to the incisal margin, and the remaining teeth were sectioned from the juncture between the most distal and most mesial points (Figs 3 and 4).

On an occlusal view of each tooth, the "distance" tool was used to measure the mesiodistal diameter between the ideal points of contact, taking into account any rotation or inclination and ensuring that the points of contact in the posterior sectors were located vestibular to the central occlusal fossa (Fig 5).

Each measurement was made twice by 2 investigators, and both sets of measurements were recorded on an Excel spreadsheet (Microsoft, Redmond, Wash). Male patients were numbered from 1 to 22, and female patients from 1 to 34. Each tooth was assigned a 2-figure number, according to the numbering system of the Fédération Dentaire Internationale (FDI).

Statistical analysis

The Dahlberg[25] index was used to calculate random errors (values were between 0.03 and 0.31 mm) of the 2 sets of measurements for each tooth in each patient. A t test for independent samples was used to evaluate systematic errors, which were found to have no significant influence on the measurements ($P = 0.05$). Table 1 shows the measurement repeatability values calculated with the Dahlberg index and the t test.

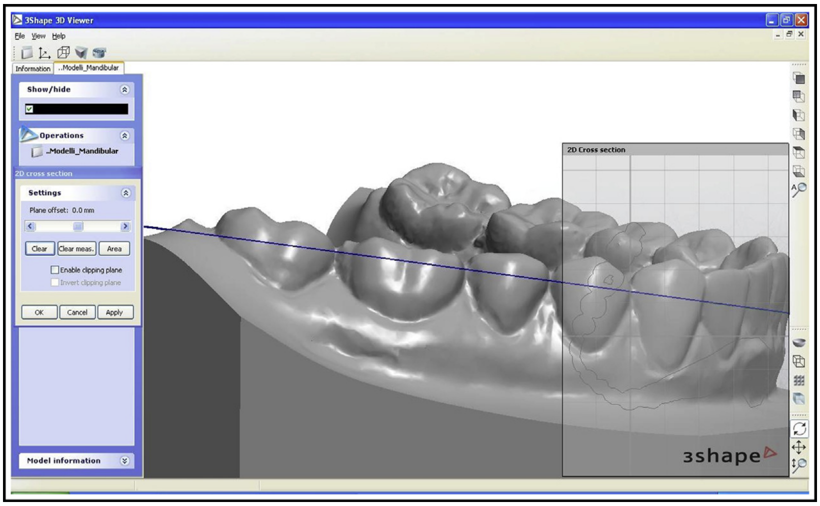

Fig 2. Vestibular view of a mandibular right first molar.

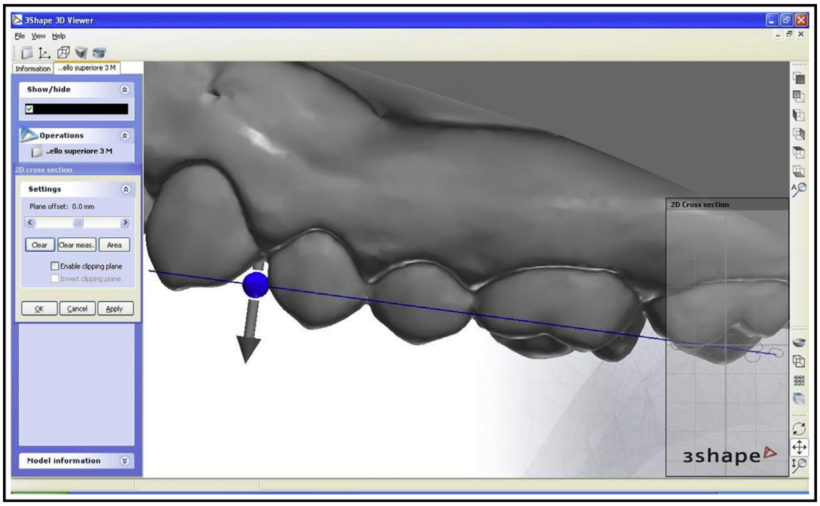

Fig 3. Plane passing through the mesial and distal contact points of a maxillary left second premolar.

A *t* test was used to compare the scores of the male and female subjects for each Bolton index (overall and anterior ratios), to calculate the differences between the mean measurements for each of the 28 teeth considered in both sexes, and to compare the left and right measurements. Because of the large number of comparisons, *P* values were corrected for multiple comparisons using the false discovery rate method.[26,27]

Subsequently, cluster analysis was applied to the data from the study sample. Essentially, cluster analysis is designed to find groups in data sets. The idea is to group items so that those in the same group, or cluster, are similar to each other, but as dissimilar as possible to items in the other clusters. The most central value of each cluster, known as the medoid, can then be identified and, with an extremely low standard deviation and possessing minimal average dissimilarity to all other values in the cluster, can be used to distinguish it from the other clusters.[28]

Separate cluster analyses were performed on data pertaining to male and female subjects, and on the maxillary and mandibular arches of each sex, with the partitioning around medoid algorithm.[28] The interdependence of the maxillary and mandibular clusters with respect to sex was determined using the Cochran-Mantel-Haenszel test.

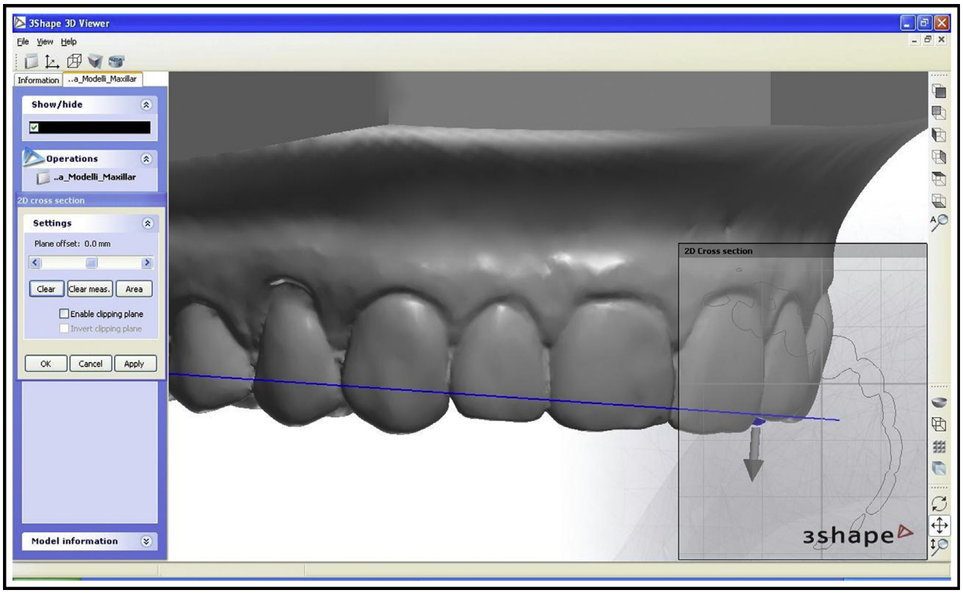

Fig 4. Plane passing through the distal contact point of a maxillary right lateral incisor, parallel to the incisal margin.

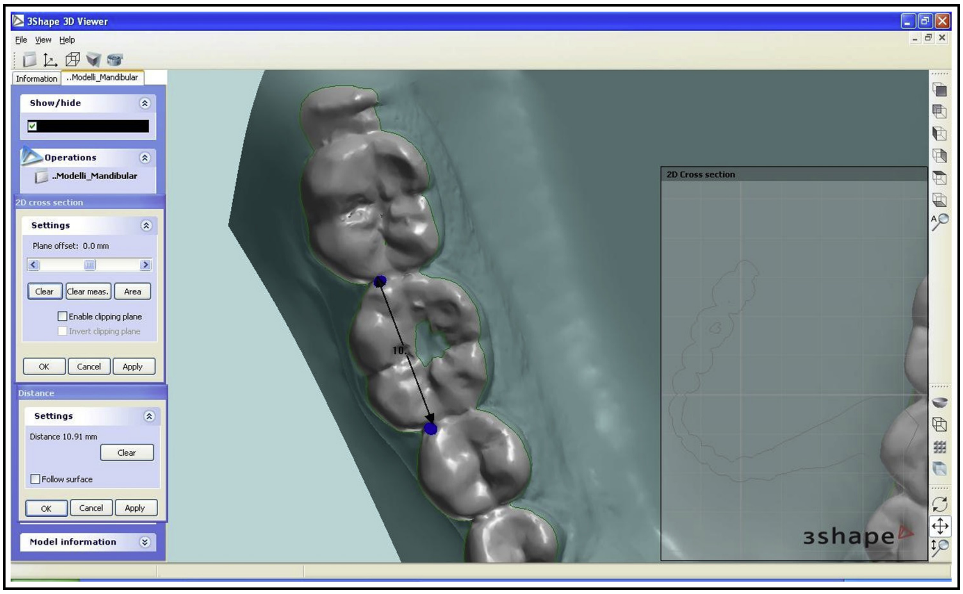

Fig 5. Occlusal view and measurement of the mesiodistal diameter of a mandibular right first molar.

RESULTS

In the preliminary analysis, we looked for the following differences.

No significant differences in either Bolton index were found between the male and female groups: anterior ratio, $t_{(37.51)} = -0.82$, $P = 0.41$, d = 0.24; overall ratio, $t_{(46.38)} = 0.66$, $P = 0.51$, d = 0.18 (Table II).

However, when teeth were measured singly, statistically significant differences between the sexes were found, as shown in Table III.

At a significance threshold of $\alpha = 0.05$, no significant differences between the left and right teeth were found, and we could therefore assume that the 2 hemispheres were comparable.

Table I. Validity of the measurements

Tooth (FDI numbers)	Mean	SD	Dahlberg's test	t value	P value
17	9.79	0.54	0.04	−0.06	0.96
16	10.31	0.46	0.04	0.16	0.88
15	6.74	0.40	0.03	0.00	>0.99
14	6.98	0.39	0.04	−0.25	0.81
13	7.70	0.43	0.03	−0.02	0.98
12	6.62	0.50	0.03	−0.07	0.94
11	8.60	0.43	0.03	0.00	>0.99
21	8.65	0.43	0.03	0.12	0.91
22	6.62	0.51	0.03	0.00	>0.99
23	7.67	0.44	0.19	−0.55	0.58
24	6.95	0.39	0.03	−0.04	0.97
25	6.74	0.40	0.03	0.00	>0.99
26	10.32	0.45	0.04	0.05	0.96
27	9.72	0.52	0.05	0.05	0.96
47	10.19	0.52	0.08	−0.06	0.96
46	10.99	0.51	0.08	0.22	0.82
45	7.15	0.34	0.06	0.22	0.83
44	7.01	0.40	0.03	−0.01	0.99
43	6.65	0.40	0.13	−0.37	0.71
42	5.86	0.36	0.10	−0.17	0.87
41	5.32	0.38	0.28	−0.83	0.41
31	5.29	0.39	0.29	−0.78	0.44
32	5.85	0.37	0.09	−0.29	0.78
33	6.68	0.51	0.31	0.42	0.68
34	7.01	0.39	0.03	0.04	0.97
35	7.16	0.38	0.07	0.05	0.96
36	11.03	0.51	0.14	0.28	0.78
37	10.15	0.53	0.09	−0.22	0.82

Cluster analysis furnished 4 distinct groups of values, and the Cochran-Mantel-Haenszel test proved the interdependence of the male and female maxillary and mandibular clusters. As in the article by Lee et al,[29] the test showed an association between them (chi-square$_{[4]}$ = 32.18, P <0.001). Nevertheless, when the criterion of Kaiser[30] was applied, it was difficult to distinguish whether there were 4 clusters or only 3. Hence, we performed the partitioning around medoid cluster analysis for both 3-group and 4-group scenarios.

Then, through multivariate analysis using the partitioning around medoid algorithm, based on the value of the average silhouette width, we discerned 3 distinct maxillary tooth clusters and 3 distinct mandibular tooth clusters (large, medium, and small) in both male and female data sets (Figs 6-9). Because no statistically significant differences were found between the left and right tooth measurements, the means of both were considered. The x-axes of Figures 6 to 9 show the tooth numbers assigned according to the FDI system, and the y-axes show the mesiodistal tooth measurements in millimeters. Medoids are represented by colored curves: blue is the large cluster, red is medium, and green is small (Tables IV-VII).

Table II. Means (standard deviation) of the Bolton indexes

	Bolton AR	Bolton OR
Men	0.7730 (0.03)	0.9157 (0.02)
Women	0.7788 (0.02)	0.9155 (0.02)

AR, Anterior ratio; *OR*, overall ratio.

Table III. Significance of the *t* test between males and females

Tooth (FDI numbers)	t value	df	Adjusted P	Cohen d
15	2.71	44.42	<0.05	0.74
13	3.87	44.45	<0.01	1.06
24	2.44	49.82	<0.05	0.65
25	3.41	48.38	<0.01	0.91
27	2.32	42.38	<0.05	0.64
47	2.83	44.36	<0.05	0.78
46	3.23	50.51	<0.05	0.85
45	3.73	42.34	<0.01	1.04
44	3.07	51.07	<0.05	0.80
43	3.57	52.00	<0.01	0.93
33	2.90	28.96	<0.05	0.89
34	3.05	52.25	<0.05	0.79
35	4.23	42.53	<0.01	1.18
36	3.00	49.94	<0.05	0.79
37	2.68	42.18	<0.05	0.75

The multivariate analysis of clusters showed a certain homogeneity in the large and small clusters. However, the medium cluster, and therefore the measurements in it, tended toward the large in both the maxillary and mandibular clusters, particularly in the men, in whom the medium and large maxillary clusters differed only in terms of the measurements between teeth 12 and 22, 16 and 26, and 17 and 27, and between 33 and 43 and 37 and 47 in the mandible. In women, on the other hand, the cluster trends were fairly homogeneous, and the medium and large clusters overlapped at teeth 36 and 46 and 17 and 27.

Analysis of variance was used to determine any statistical differences between the measurements in the 3 clusters in terms of either sex or location (maxilla, mandible). As shown in Figure 10, the maxillary values varied according to both cluster ($F_{(2.50)}$ = 95.72, P <0.001, η^2 = 0.62) and sex ($F_{(1.50)}$ = 44.48, P <0.001, η^2 = 0.14), and the measurements within the clusters also varied according to sex ($F_{(2.50)}$ = 11.07, P <0.001, η^2 = 0.07). Analogous results were also found in the mandible, where, once again, values varied in functions of cluster ($F_{(2.50)}$ = 74.85, P <0.001, η^2 = 0.56) and sex ($F_{(1.50)}$ = 61.13, P <0.001, η^2 = 0.23), and the measurements in the clusters varied in the function of sex ($F_{(2.50)}$ = 3.28, P <0.05, η^2 = 0.02) (Fig 11).

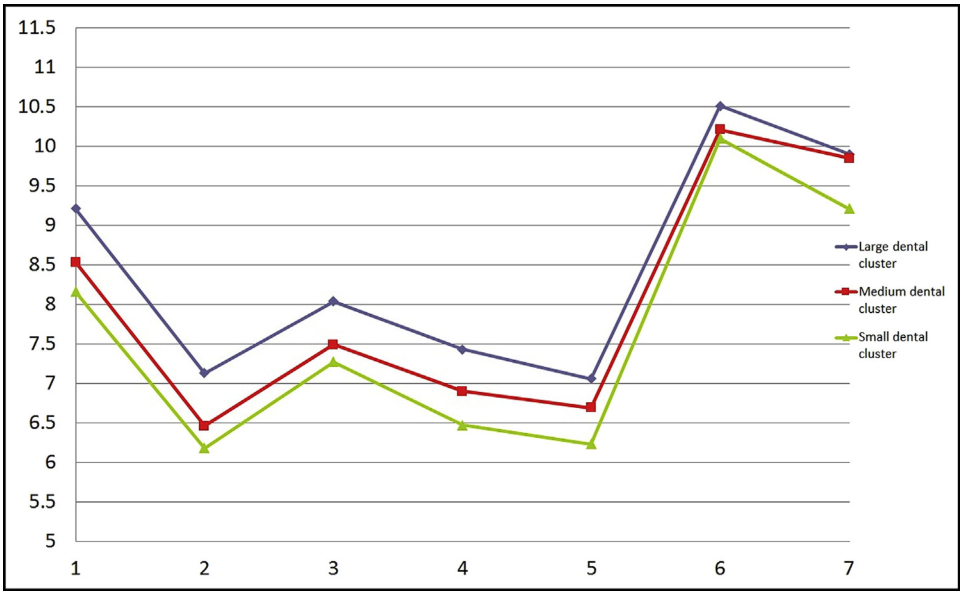

Fig 6. Maxillary tooth measurement clusters in our female sample.

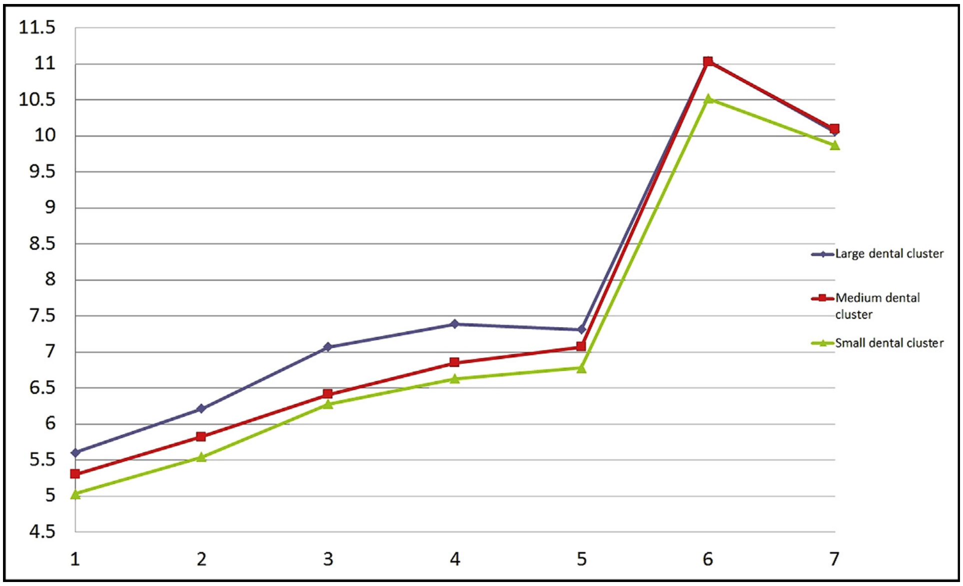

Fig 7. Mandibular tooth measurement clusters in our female sample.

For the intra-arch cluster combinations, the Bolton index was evaluated for each combination of maxillary and mandibular clusters able to guarantee the attainment of normal occlusion. The mean Bolton anterior ratio of each group varied between 0.733 and 0.810 (Table VIII), and the mean overall ratio varied between 0.891 and 0.931 (Table IX). The corresponding standards identified by Bolton were, respectively, 0.772 and 0.913. The male and female clusters that most closely fit the standards identified by Bolton are marked in gray. The empty cells indicate the combinations not considered in our sample.

DISCUSSION

Although today's orthodontists still rely on the Bolton indexes, identified more than 50 years ago, the literature is full of discrepancies regarding their applications,

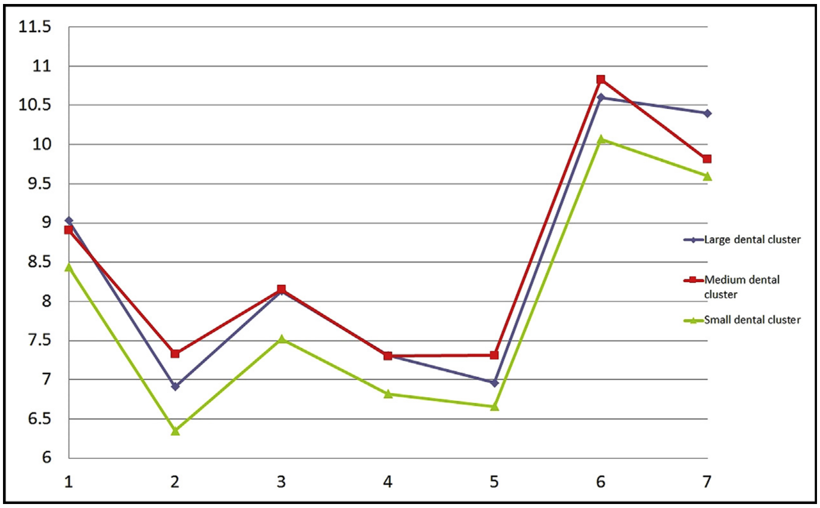

Fig 8. Maxillary tooth measurement clusters in our male sample.

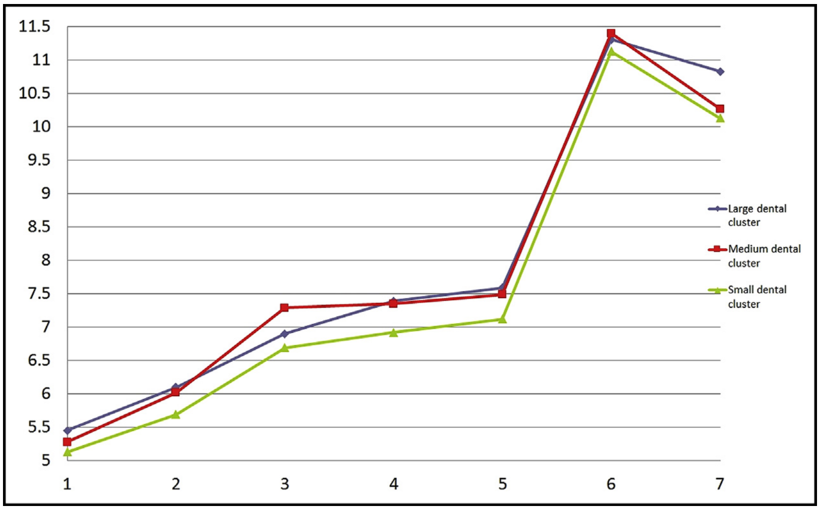

Fig 9. Mandibular tooth measurement clusters in our male sample.

particularly in terms of ethnicity and type of malocclusion. Some researchers have concluded that interarch relationships are correlated with sex, ethnicity, and type of malocclusion,[15-17,29] whereas others refute such findings.[20] Moreover, the Bolton indexes are essentially means with wide ranges of values (anterior, 74.5-80.4; overall, 87.5-94.8), indicating great interindividual variability in what is considered normal occlusion.

Hence, the use of mere statistical means to evaluate interindividual variations is not sufficient, particularly in light of the availability of modern technology and statistical tools. It is impossible to either pinpoint the location of the discrepancy or quantify it, and although 50% of cases of dentodental discrepancy can be attributed to the mandibular second premolars, maxillary lateral incisors, and mandibular central incisors, we still cannot determine the degree of discrepancy contributed by each tooth.[14] To overcome these limitations and verify the validity of the Bolton index, we therefore set out to measure the mesiodistal diameters of the teeth in our sample of 56 untreated white Italian patients with normal occlusion. We specifically chose to measure patients with no previous orthodontic treatment because they generally have an intact dentition, no extractions, and no stripping.

The 3D scanner 3Shape R700 was used to scan the plaster models of our patients because this method provides more accurate, reliable, and clinically acceptable

Table IV. Mean values (medoids) of the maxillary clusters of the female subjects

	Female subjects						
Cluster	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Large	9.21	7.13	8.04	7.43	7.06	10.51	9.90
Medium	8.53	6.46	7.49	6.90	6.69	10.21	9.85
Small	8.16	6.18	7.27	6.47	6.23	10.10	9.21

Table V. Mean values (medoids) of the mandibular clusters of the female subjects

	Female subjects						
Cluster	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Large	5.60	6.21	7.07	7.39	7.31	11.04	10.06
Medium	5.30	5.82	6.41	6.85	7.07	11.03	10.09
Small	5.03	5.54	6.28	6.63	6.78	10.52	9.87

Table VI. Mean values (medoids) of the maxillary clusters of the male subjects

	Male subjects						
Cluster	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Large	9.03	6.91	8.13	7.31	6.96	10.60	10.40
Medium	8.91	7.33	8.15	7.30	7.31	10.83	9.81
Small	8.44	6.35	7.52	6.82	6.66	10.07	9.60

Table VII. Mean values (medoids) of the mandibular clusters of the male subjects

	Male subjects						
Cluster	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Large	5.45	6.10	6.90	7.39	7.59	11.31	10.83
Medium	5.28	6.02	7.29	7.35	7.49	11.40	10.27
Small	5.13	5.69	6.69	6.92	7.12	11.13	10.13

readings than manual measurements, a process that is hampered by even slight crowding and rotation.[18,22-24] It is possible to use such digital tools to enlarge and rotate 3D renderings, without altering their effective dimensions in millimeters; this considerably facilitates the identification of the mesial and distal points of the teeth.[23]

Our digital measurements enabled us to conclude that subjects with normal occlusion consistent with the principles of Andrews[31] can have "incorrect" Bolton indexes. Although the means of the interarch relationships of our patients were comparable with Bolton's standard, the range of these ratios, both anterior (71.53-83.05) and overall (87.38-94.58), were greater than those of Bolton. This confirms the great interindividual variability in the dimensions of teeth that are nevertheless able to provide good occlusion.

Regarding the overall ratio, all combinations showed that the Bolton indexes were within the norm—ie, within the range of the standard deviations—but this was not true of the anterior ratio. Because some combinations did not display "correct" Bolton anterior ratio values, this indicates, as proposed by other authors,[29] that the Bolton index may not be a reliable indicator of good occlusion. Although the relative proportions of the maxillary and mandibular teeth are important, it is not only the mesiodistal dimensions of the teeth that affect the quality of the occlusion. The thickness of the incisal margins of the maxillary anterior teeth and the buccal cusps of the maxillary posterior teeth, the axial inclination (torque) of the teeth, and the arch form all play roles.[1,2,32] Rather than taking the Bolton indexes as absolute values (means and standard deviations), it would be wiser to take them merely as guides.

In contrast, the multivariate cluster analysis used as an alternative means of evaluating interarch dentodental discrepancy in this study enabled us to largely overcome the limitations of the Bolton method. This innovation in biomedical statistics enabled us to interpret a large data set while preserving the information relative to each measurement in it.[17,29]

Our cluster analysis yielded 4 graphs (Figs 6-9) showing the small, medium, and large clusters identified in the data set subdivided by sex and arch. These graphs could be useful as references in the orthodontic practice. A comparison of the tooth dimensions calculated for a patient with those reported in the graphs could enable us to identify, not so much the ideal relationship, but the tooth or teeth that are anomalous with respect to the normal models of tooth dimensions.

Because we found no significant differences between the left and right tooth dimensions, our graphs should be equally useful for identifying even single tooth size anomalies on either side of the arch. If, for example, a patient has a high Bolton index, without these graphs, we can only state that there is a dentodental size discrepancy between the 2 arches and cannot determine whether it is due to an excess of dental material in one arch or a lack in the other. However, using the cluster analysis graphs that are appropriate for the patient—eg, maxillary teeth of the female sample and mandibular teeth of the female sample—first, we can determine whether our patient belongs to the small, medium, or large group, and, second, we can accurately pinpoint the tooth or teeth that are anomalous with respect to the normal values in that cluster.

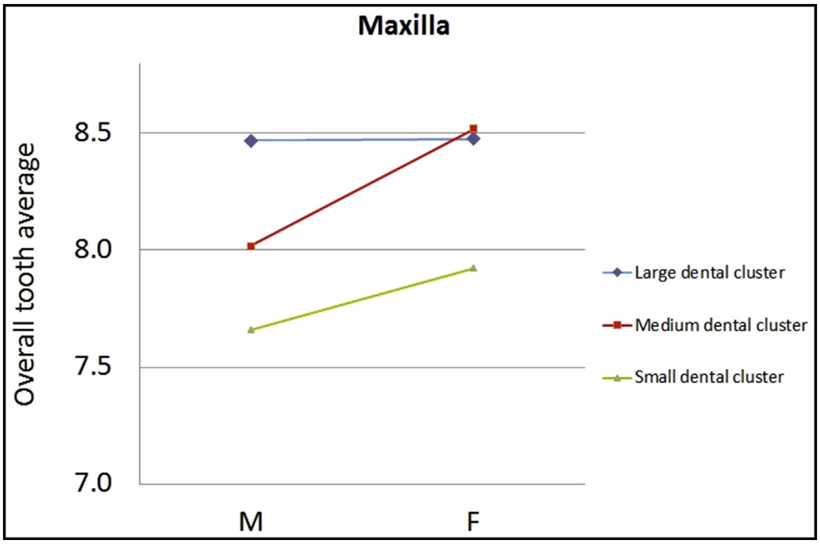

Fig 10. Graph showing how tooth dimensions vary in the functions of cluster and sex in the maxilla.

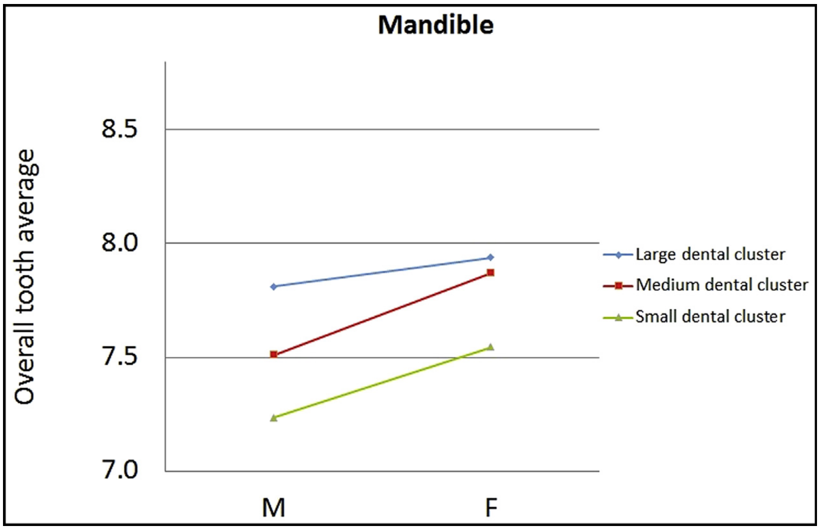

Fig 11. Graph showing how tooth dimensions vary in the functions of cluster and sex in the mandible.

This approach may also be helpful in more complex cases in which, for example, one discrepancy is found at a premolar, and it is necessary to quantify the extent of the excess or the deficit. In this case, comparison of the tooth dimensions in the anomalous quadrant with the reference graphs would immediately highlight not only the site of the discrepancy, but also its degree. To discover the extent of the discrepancy, on the y-axis, we must merely calculate the difference between the size of the anomalous tooth in our patient and that of the same "ideal" tooth on the reference graph.

These graphs show another interesting application in patients with dental agenesis. Clinicians could use the reference graphs to obtain a perfectly proportioned arch; their use could be an important aid to calculate the space needed for implant restoration.

In this study, the parallel trend in the lines divided by cluster indicates that there is a proportional relationship between the tooth dimensions in each cluster. The tooth dimensions in men tend to be larger than those in women, especially when considering the small and medium clusters, whereas in the large cluster, female patients tend to have larger maxillary and mandibular

Table VIII. Mean Bolton anterior ratio of each cluster

		Mandible		
Maxilla	*Cluster*	*Large*	*Medium*	*Small*
Women	Large	0.774	-	-
	Medium	0.793	0.776	0.764
	Small	0.789	0.807	0.768
Men	Large	0.772	-	0.734
	Medium	0.766	0.810	0.733
	Small	-	-	0.785

Table IX. Mean Bolton overall ratio of each cluster

		Mandible		
Maxilla	*Cluster*	*Large*	*Medium*	*Small*
Women	Large	0.9036	-	-
	Medium	0.9315	0.9079	0.9137
	Small	0.9233	0.9224	0.9163
Men	Large	0.9180	-	0.8911
	Medium	0.9018	0.9041	0.8939
	Small	-	-	0.9312

central and lateral incisors, maxillary first and second premolars, and mandibular canines than do the male patients.[33]

Therefore, cluster analysis is better able to evaluate the interindividual differences in such values than the simple statistical mean used to calculate the Bolton index. When we are in a position to compare our patients' measurements with a distinct medoid value for each cluster, sex and arch enable us not only to identify any interarch dentodental discrepancy (per the Bolton index), but also to differentiate on the basis of cluster and sex. Furthermore, it allows us to identify where precisely the discrepancy is found. This kind of information would be extremely useful in clinical practice because it could enable us to accurately target interventions designed to correct it (eg, stripping or interproximal reduction, or conservative addition, according to whether there is a deficit or excess of space, respectively).

There are several limitations to this study. In particular, we only considered patients with minimal crowding (up to 1.5 mm), which, although not considered clinically significant, could represent a source of bias. Furthermore, the numerous compensatory factors known to influence the interarch relationship were not considered but do merit further investigation in the future. Finally, our relatively small and homogeneous (white) sample may mean that the clusters generated here do not represent a wider population. There are several maxillary and mandibular cluster combinations missing from Tables VIII and IX and in our sample, so it is possible that these would be identified in a larger group.

Although several algorithms could be used in this type of statistical analysis, we chose a clustering algorithm because of the type of data available and the particular purpose of the analysis. For this study, and because of the size of the sample and the quality of the data, we decided that the most appropriate algorithm was data partitioning around medoids. Compared with other approaches, such as k-means, partitioning around medoids is more robust because it minimizes a sum of dissimilarities instead of a sum of squared Euclidean distances. Moreover, as reported by Lee et al,[29] it accepts a wide range of variability without removal of any data. The power of cluster analysis strongly depends on the size of the sample, and a wider group of patients, comprising those of different ethnicities, is required to test the validity of the findings of this preliminary analysis.

CONCLUSIONS

This study enabled us to draw the following conclusions regarding our white Italian sample.

1. The Bolton index is a useful tool for identifying dentodental discrepancies in most patients, even though some good occlusal relationships can be an "incorrect" anterior Bolton index.
2. The mandibular and maxillary values of our patients, both male and female, could each be divided into 3 general classes (clusters): large, medium, and small.
3. Subjects with a discrepancy between the maxillary and mandibular clusters could, nevertheless, have Bolton indexes within the normal range.
4. Comparison of the mesiodistal dimensions of a patient's teeth with the "normal occlusion" tooth clusters enabled us to determine the precise location and degree of any dental discrepancy.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.ajodo.2015.12.021.

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