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Thin-plate spline analysis of arch form in a Southern European population with an ideal natural occlusion

Matteo Camporesi, Lorenzo Franchi, Tiziano Baccetti and Antonino Antonini
Department of Orthodontics, University of Florence, Italy

SUMMARY The purpose of the present study was to identify the mean configuration of the clinical arch form in a sample of Southern European subjects with ideal natural occlusion by means of Procrustes analysis, and to compare the identified configuration with 10 commercially produced arch forms by means of thin-plate spline (TPS) analysis.

The sample comprised the study casts of 50 subjects (26 males and 24 females). The mean age of the sample was 26 years ± 4 years. All subjects were young Caucasian adults of Southern European ancestry, and presented with an ideal natural occlusion. The three-dimensional (3D) co-ordinates of all dental points (facial axis points) were digitized using a 3D electromagnetic digitizer. The morphometric technique of TPS analysis with permutation tests was used to compare the configurations of landmarks in the various specimens.

No sexual dimorphism was found for either upper or lower arch forms when the shape of the arches was assessed independently from size. The commercially available arch form that showed the least, though statistically significant, shape difference with respect to the average calculated configuration was the Brader arch form.

Introduction

With the advent of the straightwire technique and nickel titanium alloy archwires, the preformed arch has become an increasingly important part of the therapeutic armamentarium in clinical orthodontics. Several investigations have described the shape of the dental arch by means of conventional biometry by measuring angles, linear distances, and ratios (Brader, 1972; Ferrario *et al.*, 1997, 1999, 2001; Harris, 1997; Braun *et al.*, 1998; Burris and Harris, 2000; Noroozi *et al.*, 2001). This type of analysis, however, presents some limitations for the description of a three-dimensional (3D) biological structure such as the dental arch (Poggio *et al.*, 2000).

Methods of analysis that are particularly devoted to depicting shape and shape changes comprise the field of 'morphometrics'. A recent morphometric approach to the comparison of configurations of landmarks in two or more specimens is known as thin-plate spline (TPS) analysis, developed by Bookstein (1997). In TPS analysis the differences in two configurations of landmarks are expressed as a continuous deformation using regression functions in which homologous points are matched between forms to minimize the bending energy (Bookstein, 1991). Bending energy can be defined as the energy required to bend an infinitely thin metal plate over one set of landmarks so that the height over each landmark is equal to the co-ordinates of a homologous point in the other form. TPS analysis enables the construction of transformation grids that capture the shape differences and are available for visual interpretation. A detailed review of the theoretical bases, calculation procedures, assumptions, and limitations of TPS morphometrics, may be found in Bookstein (1989, 1991, 1996, 1997, 1998), Rohlf and Marcus (1993), Rohlf *et al.* (1996), and Dryden and Mardia (1998). Recently, TPS analysis has gained increasing importance in the orthodontic literature for the investigation of modifications in shape related both to facial growth and to treatment (Baccetti *et al.*, 2001; Franchi *et al.*, 2002; Alarashi *et al.*, 2003, McIntyre and Mossey, 2003).

Previous studies on dental arch shape used conventional anatomical points on the incisal edges and molar cusp tips, in order to classify dental arch forms by means of various mathematical forms such as catenary curves (MacConail and Scher, 1949), elliptic curves (Currier, 1969), paraboloids (Currier, 1969), or mixed models (ellipse and parabola) (Ferrario *et al.*, 1994), conic sections (Sampton, 1981), spline curves (BeGole, 1980; BeGole *et al.*, 1998), and the beta function (Braun *et al.*, 1998). Despite their biological significance, conventional anatomic points do not provide clinical evidence of appropriate archwire blank forms. On the contrary, landmarks taken on the vestibular surface of the teeth [facial axis points (FA points)] give direct representation of clinical archwire shape (Andrews, 1989; Fujita *et al.*, 2002) as these correspond fairly well to the position of the brackets for straightwire therapy.

The aim of the present investigation was to describe dental arch shape by means of morphometric analysis on forms determined through FA points. In particular, the purpose of the present study was to identify the mean configuration of the clinical arch shape in a sample of

Southern European subjects, with ideal natural occlusion, by means of Procrustes analysis, and to compare the identified configuration with 10 commercially produced arch forms by means of TPS analysis.

Subjects and methods

All subjects gave their informed consent to be part of the investigation.

The sample comprised the study casts of 50 subjects (26 males and 24 females) selected from the undergraduate and graduate students of the School of Dentistry at the University of Florence. The mean age of the sample was 26 ± 4 years (27 ± 4 years for males, and 25 ± 4 years for females). All subjects were young Caucasian adults of Southern European ancestry (mainly of Italian origin), and presented with the following characteristics:

1. adult dentition including the second molars;
2. bilateral Class I first permanent molar and caninerelationship;
3. overbite and overjet of 2 mm ± 1 mm;
4. absence of anterior or posterior crossbite;
5. absence of gingival recessions;
6. absence of crowding and tooth rotations;
7. absence of extensive restorations or tooth wear;
8. absence of current orthodontic treatment and negative history for previous orthodontic treatment;
9. absence of supernumerary teeth, teeth aplasia, or anomalies in tooth shape;
10. absence of deviations of the interincisal lines.

Impressions of the dental arches were taken using alginate material and were reproduced in stone and two operators (MC, LF) identified the following points on each tooth of the cast of both dental arches:

1. The FA point was defined as the midpoint on the facial axis of the clinical crown (FACC). It divides the most prominent point on the central lobe of the facial axis of all clinical crowns except for the molar teeth, where it is determined on the mesiobuccal groove (Andrews, 1989; Fujita *et al.*, 2002).
2. Interincisal points, i.e. the mesial contact point between the two central incisors.

The 3D co-ordinates of all dental points were digitized using a 3D electromagnetic digitizer (Microscribe-3DX®, Immersion Corporation, San Jose, California, USA), interfaced with a computer. The digitizer collects 3D data through a stylus tip connected to a mechanical arm that allows a full range of movements (Ashmore *et al.*, 2002). Data were recorded by pressing a foot pedal when the stylus tip was positioned on the point being captured. The data were stored in a computer using specific software (Rhinoceros® Nurbs modeling for Windows, Robert McNeel & Associates, Seattle, Washington, USA). All measurements were recorded by the same investigator (MC) with the supervision of the other operator (LF).

Using the Rhinoceros® software, the axes of the arches were traced from the interincisal point normal to a line connecting the FA points of the right and left second molars. The axes of the arches were orientated according to geometric co-ordinates (Y axis, antero-posterior; X axis, left-right, Z axis, craniocaudal). The Z co-ordinates of the points of all teeth in the mandibular and maxillary arches were reduced to zero in order to obtain a planar projection of the dental arches. All 14 FA points for every individual arch were interpolated by a line to create a planar surface for each dental arch. The planar surface of the upper and lower dental arches were orientated along the axis of the arches. The centres of gravity of all the arches were calculated by the software as the origin for the determination of the X and Y co-ordinates of the FA points for morphometric analysis.

The orthogonal least-squares Procrustes average configurations of the FA points were computed to generate the mean shape of the upper and lower dental arches. Following this method the coordinates were translated, rotated, and re-scaled iteratively until the least-squared fit of all configurations could not be further improved (Bookstein, 1991). The aim of this part of the analysis was to identify the average configuration of the dental arches in the adult Southern European sample.

The average configurations for both arches in the male subjects were compared with those in the female subjects, in order to test for sexual dimorphism in arch shape. Permutation tests with 1000 random permutations on Wilks' Lambda statistics were used to assess the significance of the differences.

In order to perform a clinical comparison of dental arch shape, as identified in the present study, with the commercially produced arch forms, offsets of 0.7 mm at the molars and 0.5 mm at the remaining teeth were introduced prior to morphometric analysis, which reflected the minimal technical thickness of the bracket bases.

To determine homologous points on the commercial wire shape for the TPS, the central points of the mesiodistal crown diameters of the permanent teeth (Moorees, 1959) were used. TPS analysis was performed using a digitizing tablet (Numonics 2210, Numonics Co., Landsale, Pennsylvania, USA), digitizing software (Viewbox© 3.0, D. Halazonetis, Athens, Greece), and morphometric software (TPS Regr© 1.28, F.J. Rohlf, Ecology and Evolution, SUNY at Stony Brook, New York, USA). Permutation tests with 1000 random permutations on Wilks' Lambda statistics evaluated the comparisons with 10 commercially produced arch forms.

Results

The average configuration (AC) for dental arch shape in the examined sample is depicted in Figure 1. No significant sexual dimorphism for either upper or lower arch shape was found.

TPS analysis revealed significant shape differences for all comparisons of the AC of dental points in both dental arches with the 10 commercially produced arch forms. Table 1 reports the Procrustes distances for all comparisons, and shows that the lowest values correspond with the Brader form in both the upper and lower arches.

In the upper arch, the commercially produced arch form that revealed the greatest significant shape difference when compared with the AC was the MBT tapered arch form (Table 1 and Figure 2A). Morphometric comparison revealed a compression in the molar region and an extension in the incisor region of the MBT tapered arch form (Figure 2A). Similar trends were assessed for the MBT ovoid arch form (Figure 2B), the tapered pentamorphic (Figure 2F), the narrow tapered pentamorphic (Figure 2G), and the narrow ovoid pentamorphic (Figure 2J) arch forms. The Tru-Arch (Figure 2E) and the ovoid pentamorphic (Figure 2I) arch forms showed significant shape differences when compared with the AC. These differences were of opposite sign with respect to the previously mentioned arch forms: a compression in the incisor region and an extension in the molar region. The MBT squared (Figure 2C) and the normal pentamorphic (Figure 2H) forms were significantly larger in the canine-premolar region and narrower in the second molar region when compared with the AC. The slight, though statistically significant, shape difference between the Brader arch form and the AC (Figure 2D) consisted mainly of a compression at the level of the canines and an extension at the level of the second premolars and molars.

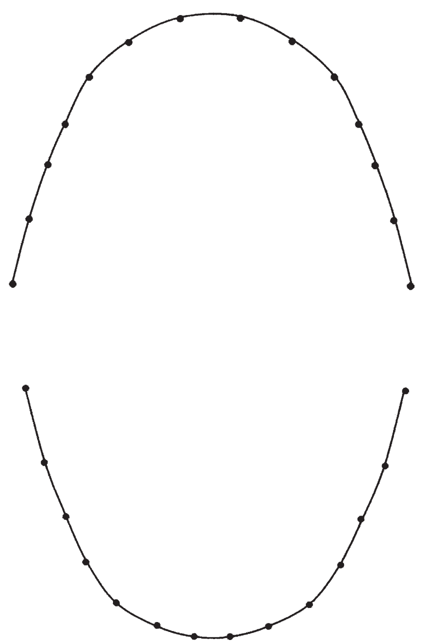

Figure 1 Procrustes average configurations of upper and lower arch forms (the dots indicate the FA points of all examined teeth).

Table 1 Procustes distances.

Commercial arch form	Upper arch	Lower arch
MBT tapered*	0.0770	0.0870
MBT ovoid*	0.0605	0.1022
MBT squared*	0.0390	0.0888
Brader†	0.0187	0.0750
Tru-Arch‡	0.0519	0.0926
Pentamorphic tapered§	0.0232	0.0795
Pentamorphic narrow tapered§	0.0616	0.1053
Pentamorphic normal§	0.0236	0.0845
Pentamorphic ovoid§	0.0338	0.0845
Pentamorphic narrow ovoid§	0.0632	0.1046

*3M Unitek, Monrovia, California, USA; †American Orthodontics, Sheboygan, Wisconsin, USA; ‡Ormco, Sybron Dental Specialties, Orange, California, USA; §Rocky Mountain Orthodontics, Denver, Colorado, USA.

In the lower arch, the commercially produced arch forms that revealed the greatest significant shape difference when compared with the AC were the MBT ovoid (Figure 3B), the narrow tapered pentamorphic (Figure 3G), and the narrow ovoid pentamorphic (Figure 3J) arches. Morphometric comparisons revealed a compression in the molar region and an extension in the incisor, canine and first premolar regions of these three types of arch forms. The MBT squared (Figure 3C), the Tru-Arch (Figure 3E), the tapered pentamorphic (Figure 3F), the normal pentamorphic (Figure 3H), and the ovoid pentamorphic (Figure 3I) forms exhibited similar tendencies. All these arch forms were significantly larger in the canine-premolar region and narrower in the second molar region when compared with the AC. The MBT tapered (Figure 3A) showed significant shape differences when compared with the AC, i.e. an extension in the incisor region and a compression in the premolar and molar regions. The lower arch form showing the least shape difference with respect to the AC was the Brader arch form (Figure 3D), which presented with a slight compression in the molar region and an extension in the incisor, canine and first premolar regions.

Discussion

Over the past 25 years, numerous investigations have analysed the dental arch form, with an anthropologic or anatomic aim (Brader, 1972; Ferrario *et al.*, 1993, 1994, 1997, 1999, 2001; Harris, 1997; Carter and McNamara, 1998). The goal being to analyse existing arch forms for orthodontic therapy (Ricketts, 1979; Felton *et al.*, 1987; Braun *et al.*, 1999; Noroozi *et al.*, 2001) or with the purpose of assessing modifications in dental arch shape induced by orthodontic treatment (Shapiro, 1974; Felton *et al.*, 1987; Germane *et al.*, 1991; BeGole *et al.*, 1998; Poggio *et al.*, 2000). The vast majority of these studies utilized conventional biometry (Brader, 1972; Shapiro,

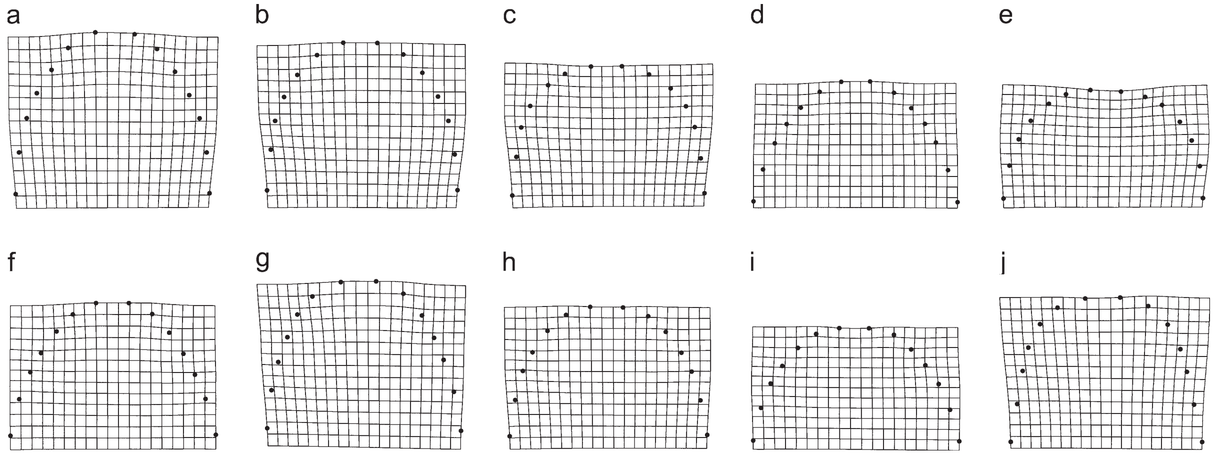

Figure 2 Comparisons of upper arch form as determined in the present sample with the following commercially produced upper arch forms: (a) MBT tapered, (b) MBT ovoid, (c) MBT squared, (d) Brader, (e) Tru-Arch, (f) pentamorphic tapered, (g) pentamorphic narrow tapered, (h) pentamorphic normal, (i) pentamorphic ovoid, and (j) pentamorphic narrow ovoid.

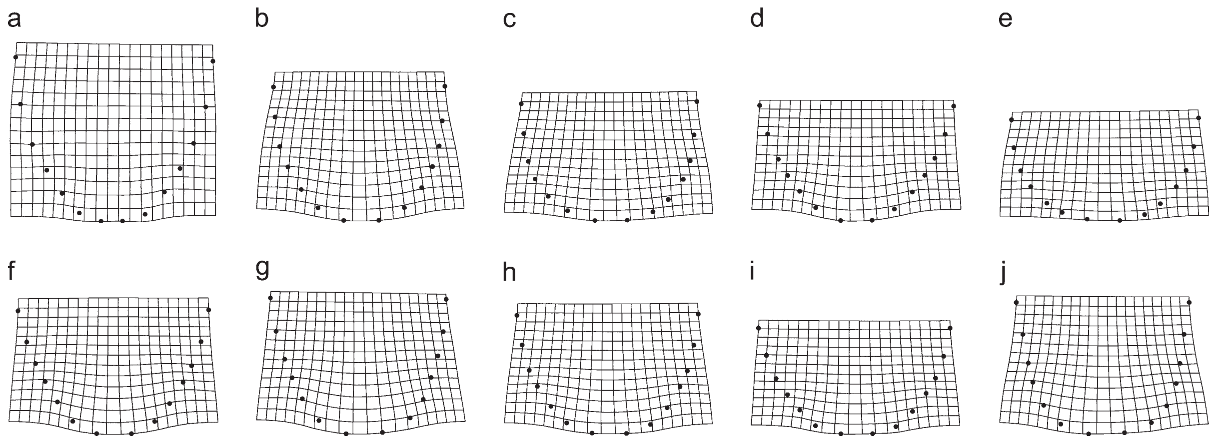

Figure 3 Comparisons of lower arch form as determined in the present sample with the following commercially produced lower arch forms: (a) MBT tapered, (b) MBT ovoid, (c) MBT squared, (d) Brader, (e) Tru-Arch, (f) pentamorphic tapered, (g) pentamorphic narrow tapered, (h) pentamorphic normal, (i) pentamorphic ovoid, and (j) pentamorphic narrow ovoid.

1974; Felton *et al.*, 1987; Germane *et al.*, 1991; Ferrario *et al.*, 1997, 1999, 2001; Harris, 1997; Braun *et al.*, 1998, 1999; Burris and Harris, 2000; Noroozi *et al.*, 2001), even though this type of analysis presents some limitations for the description of pure morphological features of biological structures such as the dental arch. Further, the description of the dental arch shape in previous investigations was based commonly on conventional anatomic points on the incisal edges of the anterior teeth, and on the cusp tips of premolars and molars (Shapiro, 1974; Felton *et al.*, 1987; BeGole *et al.*, 1998; Braun, 1998; Ferrario *et al.*, 1993, 1994, 1997, 1999, 2001; McLaughlin and Bennett, 2001). Despite their biological significance, however, these landmarks do not provide clinical evidence of appropriate archwire blank forms. On the contrary, the use of landmarks taken on the vestibular surface of the teeth (FA points) (Andrews, 1989; Fujita *et al.*, 2002) offers direct representation of clinical archwire shape. Features of note in the present study were the application of a morphometric method (TPS analysis) to the analysis of the shape of dental arches as identified through the use of FA points. The shape of the average dental arches derived from a sample of untreated Southern European subjects with good occlusion was then compared with the shape of 10 commercially available archwire forms.

The major advantages of TPS analysis over conventional biometry when comparing dental arch configurations include: (a) an optimal superimposition of landmarks for the analysis of shape without the use of conventional reference lines, and (b) a visual interpretation of the differences in archwire shape independent of size variations using transformation grids.

The present sample consisted of young adult Southern European subjects with ideal natural occlusion. Previous research has shown that there are differences in dental arch morphology between different ethnic groups (Burris and Harris, 2000). Therefore, the results have to be considered specifically for European populations of the Mediterranean area. An initial finding of the present study revealed no significant differences in shape between males and females for both the upper and lower arches analysed using TPS analysis. This result is in agreement with previous morphometric data (Ferrario *et al*., 1993), who did not find sexual dimorphism in the dental arches when evaluated by Euclidean-Distance Matrix Analysis. For this reason, the data concerning the analysis of average configurations of the dental arches in males and females were pooled in the present study.

According to the results of this investigation, the shape of the vast majority of dental arch forms that are available commercially is significantly different from the average configuration of the ideal natural occlusion as revealed from this sample of Southern European subjects. Some of the arch forms were more extended in the region of the incisors and more compressed in the region of the molars, while others showed an opposite tendency. The arch forms that had the least morphological differences with respect to the group under investigation were the Brader forms, which still presented with a slight compression in the molar region and an extension in the incisor, canine and first premolar regions.

Due to the nature of the morphometric technique employed in this study, the average configurations derived from the examined sample population describe solely the 'shape' features of the dental arches. By definition, these data are independent from 'size'. The dimensional analysis of the arch forms in the Southern European sample revealed that the average distance between right and left second molars (measured at the FA points with the correction of offsets due to band/bracket thickness) was 62 mm in the upper arch, and 59 mm in the lower arch. The mean distance between right and left canines was 38 mm in the upper arch, and 30 mm in the lower arch. It appears, from a commercial point of view, the average forms along with the options of 5 per cent enlarged forms and 5 per cent reduced forms are to be recommended.

Conclusions

The present morphometric study evaluated the average arch forms for the upper and lower dental arches in a sample of Southern European young adults with ideal natural occlusions. The analysis of the calculated arch forms indicated that:

1. There were no sexual dimorphism for either upper or lower arch forms when the shape of the arches was assessed independently from size;
2. The commercially available arch form that showed the least, though statistically significant shape differences with respect to the average calculated configurations, was the Brader arch form.

Address for correspondence

Lorenzo Franchi
Dipartimento di Odontostomatologia
Università degli Studi di Firenze
Via del Ponte di Mezzo, 46–48
I-50127 Firenze
Italy
E-mail: l.franchi@odonto.unifi.it

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