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Dental arch monitoring by splines fitting error during orthodontic treatment using 3D digital models

Praćenje oblika zubnog luka odstupanjima fitovanih splajnova tokom ortodontske terapije primenom 3D digitalnih modela

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Abstract

Backrgound/Aim. Researchers in the field of dentistry have been conducting research into modelling and defining dental arches equitations. Nowadays, when 3D digital modelling is commonly utilized in dentistry, the approach to modelling, analysis and synthesis has changed. Clinical researches are related to aesthetic and functional analysis. The aim of this study was to increase repeatability and accuracy of defining and determining the coordinate system of the jaw as well as to defining mathematical criteria for monitoring and evaluating orthodontic treatment. **Methods.** In this study, we used the plaster models of the jaw, optical scanner with structured light, 3D digital models, computer aided design (CAD) engineering tools adjusting the coordinate system, spline fitting of 3rd, 4th, 5th, 6th, 7th and 8th degrees. **Results.** Splines of 3rd, 4th, 5th, 6th, 7th and 8th degrees were fitted from the initial state (K0) in all 10 successive controls (K1, K2, K3,…, K10). All splines were fitted through 12 points, from the right to the left side of the jaw: 6-5-4-3-2-1-1-2-3-4-5-6. Tabular and graphic presentations of the maximum and average deviation of dental arch fitting curves in successive controls were given. **Conclusion.** The parameters of the maximum and average errors of fitting curves converge the dental arch values that are lower than the accuracy of the used optical scanners. The average error of fitting provides a general picture of the entire dental arch at each stage of treatment. Maximum error fitting points at a specified tooth where the largest deviation.

Key words:
computer-aided design; dental arch; jaw; malocclusion; orthodontic appliance design.

Apstrakt

Uvod/Cilj. Istraživači u oblasti stomatologije, posebno kliničari, već dugo se bave istraživanjima koja se odnose na modeliranje i definisanje oblika i parametara zubnog luka. Danas, kada je 3D digitalno modeliranje postalo uobičajena praksa u stomatologiji, promenio se i prilaz modeliranju, analizi i sintezi u ortodonciji. Klinička istraživanja oblika zubnog luka direktno se odnose na estetsku i funkcionalnu analizu zubnog niza (nivelacija, okluzija, zagrižaj). Cilj rada bio je da se poveća ponovljivost i preciznost definisanja i određivanja koordinatnog sistema vilice i definišu matematički kriterijumi za praćenje i ocenjivanje ortodontske terapije. **Metode.** U radu su koršćeni gipsani modeli vilice, optički skener sa strukturisanom svetlošću, 3D digitalni modeli vilice i *Computer Aided Design* (CAD) i inženjerski alati. Sprovedeno je podešavanje koordinatnog sistema i fitovanje splajnova trećeg, četvrtog, petog, šestog, sedmog i osmog stepena. **Rezultati.** Splajnovi (trećeg, četvrtog, petog, šestog, sedmog i osmog stepena) fitovani su u odnosu na početno stanje (K0), za svih 10 uzastopnih kolona (K1, K2, K3,... K10). Svi splajnovi su fitovani u 12 tačaka, sa leve i desne strane vilice: 6-5-4-3-2-1-1-2-3-4-5-6. Dat je tabelarni i grafički prikaz maksimalnih i prosečnih odstupanja fitovanih krivih linija dentalnog luka u sukcesivnim kontrolama. **Zaključak.** Parametri maksimalne i prosečne greške fitovanja krivih linija dentalnog luka konvergiraju vrednostima koje su manje od tačnosti korišćenih optičkih skenera. Prosečna greška fitovanja daje opštu sliku celokupnog dentalnog luka u svakoj od faza terapije. Maksimalna greška fitovanja ukazuje na tačno određeni zub gde su odstupanja najveća.

Ključne reči:
kompjuterski podržan dizajn; zubni luk; malokluzija; ortodontski aparati, dizajn.

Introduction

3D digital modelling is widely used in orthodontics today [1,2] for the following: laser scanning and computer aided design (CAD) modelling of complex shapes and surfaces, teeth and jaws, as a separate area of engineering modelling, analysis and synthesis of orthodontic parameters in 3D digital and plaster models (precision, repeatability, validity,

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reliability), occlusion analysis, planning and monitoring orthodontic treatment and analysis and synthesis of dental arch shape.

A specific example of research [3] involves comparisons of the dental arch shape for its axis in relation to its crown and root end, of classes 1 and 2, of the group 1 of malocclusion, using WALA points [4] and by WALA points, orthodontic treatment can be successfully planned.

The measurement and analysis of 20 models (virtual, plaster) was done with the following parameters: mesiodistal tooth width, intercanine and intermolar distance, as well as the width of the arch [5]. Nonparametric statistics showed that, from the aspect of precision and repeatability of results, the utilization of the OrtCAD was greater than in conventional measurements on plaster models.

The analysis of the ideal dental arch shape, showed a fourth degree polynomial, and in case of patients missing a tooth (particularly from the first molar to the central incisor), β function represented a better solution for the simulation of dental arch shape [6].

A research by Park et al. [7] provided results regarding the new classification of dental arch shapes in an ideal bite, obtained by 3D digital models and the cluster analysis (divided into 4 clusters, based on the orthodontic parameters) of the classification of dental arch shapes with distances: between canines, premolars and molars.

The study by Slaj et al. [8] showed the dental arch shapes obtained by the factor analysis of 137 digital models. The key element of factor analysis was the ratio between the lower canine width/height, which comprises 82.8% of variability ($p < 0.001$). The dental arch shape in the lower jaw was substantially different in posterior teeth, whilst in the upper jaw the greatest changes were observed in anterior teeth.

A combined method of determining a dental arch by superimposition in the lower jaw, using two techniques – cone beam computed tomography (CBCT) and 3D modeling was shown in the study by Park et al. [9]. The results of the research showed that 3D modelling is a simpler and more reliable means for calculating the length of the dental arch.

A comparison of precision of 3-dimensional models was obtained by an intraoral scanner, 3D digital model and conventional measuring [10]. The obtained dental arch length for the 3D models was: precision – 1.6 ± 0.6 μm and validity – 5.3 ± 1.1 μm. The same parameters for intraoral scanner were 12.5 ± 2.5 μm and 20.4 ± 2.2 μm, and for conventional measuring they are 32.4 ± 9.6 μm and 58.6 ± 15.8 μm. In all these analyses $p < 0.001$ was the same.

Finally, the digital models provide reliable and clinically dependable orthodontic parameter results for the tooth width, dental arch circumferences, intercanine and intermolar widths [11]. The conclusion is that the digital model produces a lower degree of variation in the measured results compared to the conventional measuring method in the Little's Irregularity Index.

The research by Kook et al. [12] dealt the measurements on the 3D models and plaster impressions of 7 dental arch parameters (width/distance of the first 6 maxillary teeth, left and right) in a sample of 27 patients. The overlapping parameter showed significant statistical differences, which confirmed the impact of brackets on the 3D models. The conclusion is that the overlapping parameter should be carefully considered and measured in future while paying a special attention to the position of each individual tooth.

AlHarbi et al. [13] suggested that, in order to ideally describe the dental arch curve, a polynomial of a higher degree had to be used. This curve should possess a significant flexibility, so it can be adjusted to suit any dental arch size and had to include the jaw asymmetries, if any. Starting from the fact that a dental arch is an imaginary curve, the descriptive information, i.e., function represents a set of discrete points. For that reason, a mathematically obtained curve should be adjusted to the individual points [14, 15]. This approach refers to the curve adjustment or interpolation. Curve adjustment is a concept used for adapting the mathematical shape of a curve to the curve of the actual dental arch shape. The curve generated by proposed mathematical functions is adjusted in accordance with marks on the teeth believed to precisely define the dental arch. With the aim of discovering the optimal mathematical function to describe the dental arch curves, a number of authors tested various mathematical functions (models) which could best serve this purpose. Some of these models are: conic curve shapes, U-curve, cubic equations, equations from 2nd to 8th degree, mixed models and the beta function [16, 17]. Finally, it is difficult to generalize their findings or draw conclusions for a number of reasons: different objectives, different study samples with different criteria and different methodology.

This analysis helps us conclude that the analysis and synthesis of dental arch are elements of overall orthodontic treatment. However, all researches investigate groups of patients, whereby the general or common characteristics can be determined.

The previous analysed studies [18–20] did not consider adjusting the coordinate system of the jaw. Probably the reason is the American Board of Orthodontics (ABO) [18] recommendations published for the first time in 2013 and the latest version was published in 2016. Comparisons of dental arch curves is not possible if the coordinate system is not defined uniquely and the repeatability is not provided in all successive controls.

The first objective of this study was analysis and improvement of the ABO recommendations. The second objective was the definition of mathematical criteria for monitoring and evaluation of orthodontic treatment. For this purpose, the maximum and average fitting errors of dental arch curves, interpolating splines of 3rd, 4th, 5th, 6th, 7th, and 8th degrees will be monitored.

In existing literature, there is no extensive mathematical analysis of the dental arch shape in persons with normal occlusion in the course of orthodontic treatment. Therefore, the aim of this study was also to define the dental arch function as a polynomial, from 3rd to 8th degree, and to perform its thorough analysis following all the stages of orthodontic treatment. The core of the problem is that during the treatment, the position of teeth in the jaw changes, which leads to a change in the position of coordinate system of the jaw, based on which the function of dental arch is modelled. The consequence of this is that the shapes of the dental arch for two conditions – stages of treatment – can be compared with a relatively low precision. As a result, here we established a global coordinate system of the jaw (GCSJ) following the advanced method of ABO, thereby eliminating this negative impact, so that the dental arches can be absolutely accurately compared at each individual stage of orthodontic treatment. This research represents a part of the overall model for monitoring and analysis of orthodontic treatment, from the aspect of teeth alignment, using the 3D digital models [1].

Methods

This study includes scans of 22 impressions, obtained from the patients' archives at the Clinic for Jaw Orthopaedics, Faculty of Dentistry in Belgrade, using the ATOS scanner [21], with the precision lower than 10 µm. The impressions were randomly chosen. The only criterion was normal occlusion. 3D modelling was performed by the Siemens NX10 software [22].

The curved lines describe the dental arch in normal occlusion, meaning it is in X-Y (occlusal) plane in the orthodontic coordinate system of the jaw digital model, called GCSJ [1]. It is defined by ABO rules [18], which state digital model requirements and these instructions represent a commonly accepted *de facto* world standard for digital models of jaws. In accordance with the guidelines, the digital models were generated in the PLY, STL or OBJ format files, from which further analyses were performed. In addition, the scanners used for generating the 3D digital models need to have resolution of 0.10 mm or more and precision [18] of at least 0.20 mm. One of the basic characteristics of the procedure for determining GCSJ is that it provides the repeatability of measuring (scanning) one jaw model on different scanners, which is extremely significant for the 3D digital models. On the other hand, when comparing several different jaw models, which occurs in the course of an individual patient's orthodontic treatment, the ABO guidelines do not provide enough precision. This is mostly related to defining Y-axis orientation (Y-Z: median plane) and zero – the origin of coordinate system. This paper improved the ABO guidelines, thereby also enhanced the results of our research.

Digital model orientation and coordinate system definition

The ABO defines requirements for digital models (scan resolution and accuracy, measuring units, file formats and mesh topology) and the procedure for adjusting the coordinate system [18].

Defined procedure, in essence, is very similar to the procedures used by engineers in coordinate metrology. This is quite logical, because this is completely an engineering problem. The jaw coordinate system adjusting procedure is a typical "3-2-1" procedure. Numbers "3-2-1" in the procedure name define degrees of freedom that are fixed in each of the three steps. To define the coordinate system exactly, it is necessary to fix all 6 degrees of freedom (3 rotations and 3 translations) and how much of each solid body decoupled [19]. ABO "3-2-1" procedure is related to: XY plane – occlusal: fitting a plane using the least squares method through 16 points (molars and premolars cusp tips); Y axis orientations, mid-sagittal: through the mid-points of line segments between 2 left +2 right points located in the mid-palatal raphe; Origin (0,0,0): at a point that lies approximately half-way between the most anterior and most posterior teeth.

The ABO procedure has two major drawbacks: it is not possible to provide a satisfactory repeatability of Y axis orientation in successive controls of a patient jaw; the origin position is not precisely defined. During the treatment the incisors are the most shifted teeth; their intake for reference is completely wrong. The ABO procedure uses the term "approximately" for origin position. "Approximately" it is not good enough for accurate measurement, especially in the case of dental arch creation and their comparison in successive controls.

The ABO procedure provides repeatability when one unchanged jaw model is scanned [18] by using different scanners. This is not the case when monitoring the entire orthodontic treatment. To be able to compare the scanned models of two successive check-ups, it is essential that the coordinate systems is always in the same position. It is an axiom of coordinate metrology. If we want to compare the equations of dental arch, as it was done in this paper, adjusting the coordinate system is the most important step in the entire procedure. Mistakes made in the initial step inevitably lead to wrong conclusions. The erroneous coordinate system settings have the greatest impact on the measurement error [19].

The ABO procedure described deficiencies; they are enhanced by the new determination of the Y axis direction, and more accurate determination of the origin. Figure 1 shows these improvements.

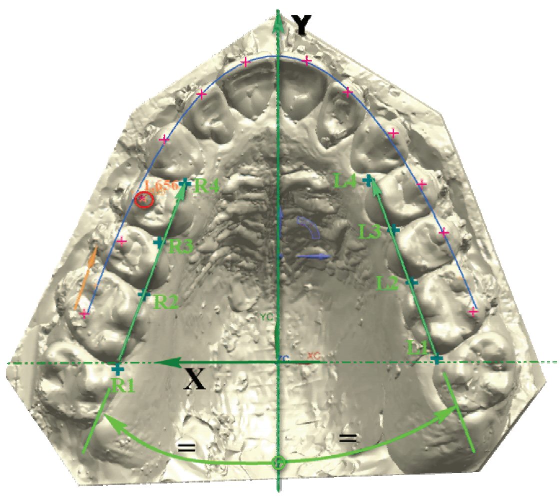

Fig. 1 – Jaw coordinate system definition.

Y axis is the bisector of two lines on the left and right side of the jaw (Figure 1). Each line is interpolated through 4 points using the least squares method. On the right side these interpolating points are marked in Figure 1 in the following way: R_1-R_2-R_3-R_4. On the left side these interpolating points are marked in Figure 1: L_1-L_2-L_3-L_4. Pairs of points (R_1-L_1 and R_4-L_4) were determined in the same way as defined in the ABO guide [18]. Additional pairs of points R_2-L_2 are defined in a similar way and they are located between 4th and 5th tooth on the right and left side, respectively. Additional pairs of points R_3-L_3 are located between 5th and 6th tooth on the right and left side, respectively. A new improved method uses 8 points (4 + 4) for the Y axis definition; the ABO guide uses only 4 points (2 + 2) for the Y axis definition. A larger number of points improve repeatability of the Y axis settings.

Coordinate system origin is fixed as the intersection between previously determined Y axis and temporary auxiliary line defined by the points R_1 and L_1, as shown in Figure 1. Intersection point defined the origin (0, 0, 0). X axis is perpendicular to Y axis, and its direction is defined by the right-hand rule. X axis, as expected, does not pass through points R1 and L1. The human body is never perfectly symmetrical.

The origin is determined by the position of the molars, which cannot be displaced (or very minimally). The incisors are the most displaced teeth during orthodontic treatment and should not be taken as a reference for coordinate system origin.

In this paper, interpolation (fitting) curves over all digital models of the upper and lower jaw were made over the same set of digital models presented in the study by Majstorović [1], as already mentioned.

For the fitting curves which define the dental arch we used the Computer Aided Design, Computer Aided Manufacturing, Computer Aided Engineering (CAD/CAM/CAE) system by world renowned medical equipment manufacturer – Siemens. The software Siemens NX10 is used for the general purpose[22]; it is primarily intended for applications in mechanical engineering. Its flexibility and openness of the architecture allows it to be easily applied in very different areas. Its advantage over the specialised software packages in the area of orthodontics is its dedication to sophisticated modules for the complex spatial forms (free-form, sculptured surfaces).

All splines created with Siemens NX10 are [22] the Non Uniform Rational B-Splines (NURBS). The literature providing a mathematical foundation [20] is widespread and easily accessible. Splines are widely used, not only in various engineering areas. Their utilisation in the CAD/CAM/CAE systems is simple and intuitive. There is no modern CAD/CAM/CAE system that does not include the ability to create splines. In this section, the terms "B-Spline" and "Spline" are used interchangeably. There are three creation methods for splines (Figure 2): by poles – causes the spline to gravitate towards each data point (that is, pole), poles form a control polygon which determines the shape of spline; through points: the spline passes through a set of data points; fit: the spline does not necessarily pass through the points, except at the endpoints.

In this study, splines were fitted through the points of digital models, which are located at the tips of the teeth (from the right to left side): 6-5-4-3-2-1-1-2-3-4-5-6; marked in Figure 3. A total of 12 points are used for all the interpolations. As shown in Figure 1, interpolated curve does not pass through the points on the digital model. Some points are closer to the curve, others are away from it. Siemens NX10 marks the most distant point from the fitted curve. In the example in Figure 1, the point with maximum deviation is marked with a small red circle. Siemens NX10 shows the value of the maximum deviation; Figure 1 shows that this value is 1.656 mm on the fourth tooth on the right side. This is a clear indicator for the dentist which tooth to pay more attention to. In addition, Siemens NX10 gives the value of the average deviation of all points on the fitted curve. The user has information on the average deviation, maximum deviation value and the location of maximum deviation.

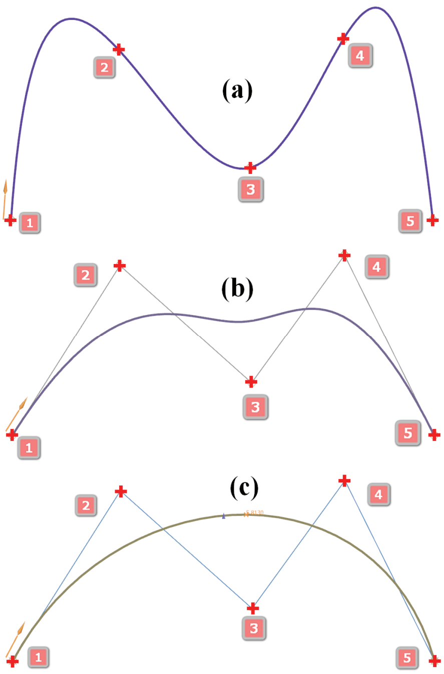

Fig. 2 – Spline interpolation methods: a) through points, b) by poles, c) Fit.

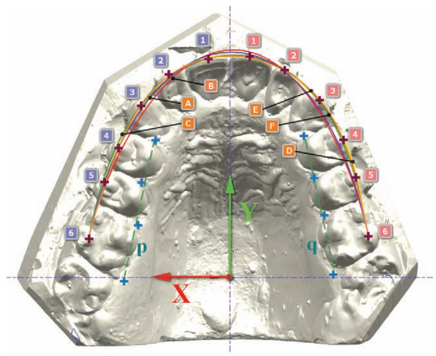

Fig. 3 – Dental Arch Fitted splines. Label A: 3rd (purple); Label B: 4th (red); Label C: 5th (green); Label D: 6th (yellow); Label E: 7th (orange); Label F: 8th (brown) degrees.

Another important aspect is the degree of the fitted spline. Every spline has a degree – a mathematical concept referring to the degree of the polynomial that defines the curve. The degree is generally one less than the number of points in a spline segment [22]. For this reason, it is not possible to have a spline with fewer points than the degree. A higher degree curve is stiffer in the sense that its poles have to be moved a long way to produce any appreciable change in the shape of the curve. Lower degree curves are more pliable, and tend to follow their poles much more closely.

Figure 3 adequately illustrates the problem of selecting the degree of fitted curve of dental arch. The figure shows the interpolated splines from 3rd to 8th degrees.

Zero or a very small value (smaller than the accuracy of the scanner) of average and maximum deviation of the fitted spline for dental arch is a clear indicator that the treatment is reaching its completion.

Thanks to the computer speed and implemented algorithms, several spline fittings can be instantly executed. The user (dentist) interpolates splines of 3rd, 4th, 5th, 6th, 7th and 8th degrees in all stages of orthodontic treatment. This activity can be carried out automatically and does not require any additional knowledge or training.

The convergence of the maximum and average deviation of the fitted splines are the criteria for selecting appropriate curve's degree. The curves whose degree is not suitable will not converge but diverge.

A key requirement is the constancy of the position of the coordinate system. If this condition is not fulfilled, the comparisons are not possible. As already pointed out, the adjustment of the coordinate system is a critical step. Errors made in the initial step lead to wrong conclusions. Therefore, a special attention needs to be paid to a problem of the coordinate system adjustment.

Results

The developed method was applied on a patient undergoing orthodontic treatment. In each of the stages of the treatment an impression was taken on the basis of which a plaster model was created. All plaster models were scanned using optical scanners [23] in the Standard Tessellation Language (STL format – stereolithography). The obtained digital models were transferred onto engineering software [22] where they served as a basis for the application of previously described method.

The original state (without the fitted braces) was marked as "K0". Each of 10 check-ups was performed in an interval of one month (of wearing braces).

Splines (3rd, 4th, 5th, 6th, 7th and 8th degrees) are fitted from the initial state (K0) in all 10 successive controls (K1, K2, K3, …, K10). All splines were fitted through 12 points, from the right to the left side of the jaw: 6-5-4-3-2-1-1-2-3-4-5-6. The points for interpolation are marked with red crosses in Figure 3. Each interpolated spline at its beginning has a slope of line "p" and at its end has a slope of line "q", as shown in Figure 3. The bisector line "p" and "q" determines the Y axis direction as explained in the chapter "Adjusting the coordinate system of the jaw".

For each fitted spline Siemens NX10 gives to the user the following information set: value of the Average Fitting Error, value of the Maximum Fitting Error and indicates with an asterisk which points have the maximum value of fitting error. The values obtained for all 11 digital models are presented in Table 1. Column "Deg." indicates the degrees of fitted splines. Column "Err." is divided into two rows marked" M" and "A" for each degree of interpolated splines. "M" stands for Maximum Fitting Error and "A" stands for Average Fitting Error. Columns "K0, K1, K2, K3, K4, K5, K6, K7, K8, K9, K10" indicate all stages of the orthodontics treatment.

The values from Table 1 are shown in the diagrams. The diagram of the maximum deviations for all check-ups is shown in Figure 4. The diagram of the average deviations for all check-ups is shown in Figure 5. The horizontal axis represents the stage of the orthodontic treatment. The vertical axis shows the deviation in mm. Each degree of fitted splines is displayed in a different colour and marked with different graphic symbol (legend of symbols is shown in the diagrams).

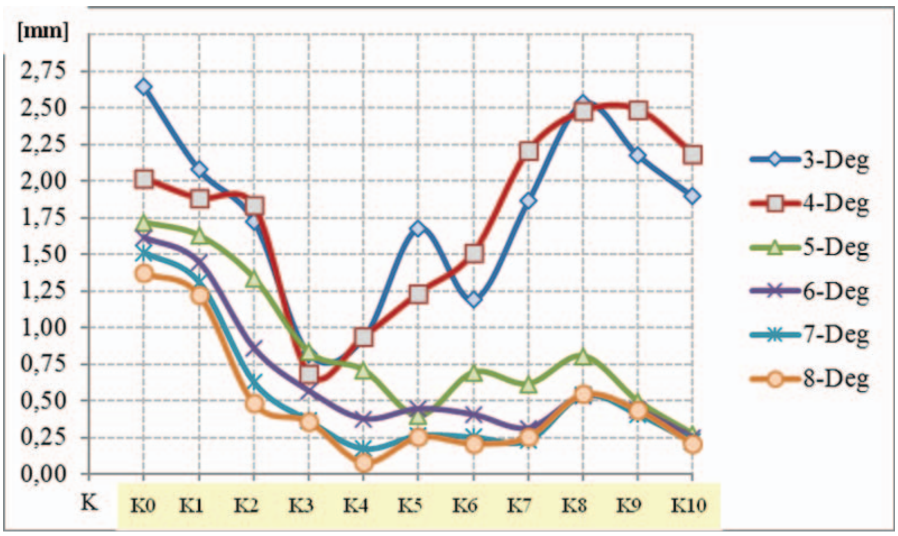

Fig. 4 – Maximum error fitting deviation diagram.

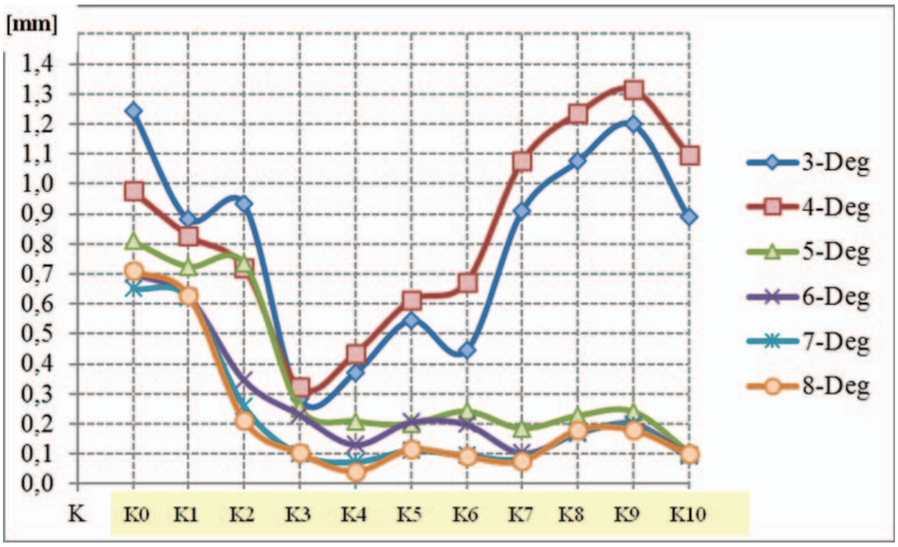

Fig. 5 – Average error fitting deviation diagram.

It is noticeable that the values of the maximum and average deviation of fitted splines of 3rd and 4th degrees diverge. A clear conclusion is that the 3rd and 4th degrees of curves are not appropriate for this patient.

Higher degree splines (6th, 7th, 8th) define a good dental arch of the patient. Table 1 shows that the best result had the 6th degrees spline (10th check-up): maximum deviation was 0.247 mm at the left incisor; average deviation was 0.097 mm. The obtained value of the average deviation was smaller than the accuracy of the used scanner. Figure 6 shows the interpolated spline of 6th degree after the 10th check-up.

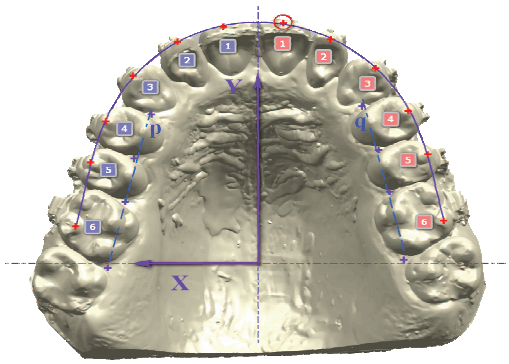

Fig. 6 – Dental arch; 10th control; 6th degrees fitted spline.

Table 1

Values of maximum and average splines fitting errors (Err) in mm

Deg.	Err.	K0	K1	K2	K3	K4	K5	K6	K7	K8	K9	K10
3	M	2.642	2.078	1.727	0.820	0.927	1.679	1.188	1.862	2.529	2.175	1.895
	A	1.244	0.882	0.934	0.285	0.372	0.547	0.446	0.910	1.076	1.199	0.891
4	M	2.016	1.879	1.831	0.681	0.935	1.232	1.508	2.205	2.475	2.486	2.186
	A	0.976	0.828	0.721	0.322	0.436	0.612	0.673	1.075	1.236	1.314	1.099
5	M	1.717	1.627	1.337	0.830	0.707	0.397	0.692	0.613	0.804	0.495	0.271
	A	0.811	0.726	0.737	0.253	0.209	0.199	0.243	0.185	0.227	0.242	0.106
6	M	1.615	1.446	0.858	0.566	0.376	0.444	0.404	0.312	0.531	0.435	0.247
	A	0.702	0.623	0.346	0.231	0.132	0.207	0.199	0.104	0.168	0.202	0.097
7	M	1.510	1.308	0.627	0.364	0.173	0.262	0.252	0.226	0.538	0.406	0.219
	A	0.651	0.622	0.260	0.099	0.074	0.112	0.096	0.086	0.172	0.195	0.091
8	M	1.373	1.225	0.483	0.360	0.079	0.253	0.208	0.255	0.544	0.436	0.206
	A	0.711	0.630	0.213	0.103	0.042	0.115	0.091	0.077	0.180	0.180	0.099

Deg. – degrees of fitted splines; "M" and "A" – degrees of interpolated splines. M – maximum fitting error and A – average fitting error. K0, K1, K2, K3, K4, K5, K6, K7, K8, K9, K10 indicate all of the phases of the orthodontics treatment.

Discussion

The fact is that modern medicine and dentistry cannot be imagined without the involvement of mechanical and electrical engineers. This research is an example of the interdisciplinary engineering modelling and its applications in orthodontics [23].

There is a large number of studies considering appropriate mathematical equations to define the dental arch. Some of these studies have examined hundreds of patients. The shape of the dental arch depends on gender, age, ethnic background and so on. However, several hundred patients are still too small a sample for the population of a couple of million. It is very difficult and unreliable to try and draw general conclusions because the critics argue that "the sample is too small". Large studies can not generate results regarding an individual. It is necessary for an appropriate government institution to realise this in the next couple of decades.

Due to the previously stated reasons, the authors of this study started from the premise that each individual is a subject unto itself. Personal orthodontics finds the appropriate equation of dental arch for each person separately. For some person 3rd degrees equations will be the most appropriate, for other 6th degrees and so on. The shape of the jaw bone is the most appropriate template for the equation of the dental arch.

It is hard to say which of the displayed curves (in Figure 3) is the most appropriate. Selection of the curve's degree is often very subjective. Is it possible to define an objective mathematical criterion for selection? Is there a mathematical criterion for the orthodontic treatment to be conducted in the desired direction and to the desired objective? The authors developed a method that gives a positive answer to the previous question.

Precise determination of the global coordinate system of the jaw as well as its accurate repeatability [23, 24] is the key to defining the curve that delineates the dental arch. An error in the initial step of determining the coordinate system becomes systematic and cannot be eliminated. If a coordinate system of the jaw is not accurately determined in all successive check-ups, then those check-ups cannot be reliably compared. The obtained results regarding the advancement of orthodontic treatment can be entirely wrong.

Another highly significant aspect is defining and setting of referent geometric entities [2]. They need to be always placed in the same location, in every 3D model generated for each controls. Random setting, or rule of thumb, does not generate precise results. An error in setting of even a single entity leads to more mistakes it is hard to correct, and even more importantly, difficult to detect.

It is noticeable from the results of the case study that the values of the maximum and average deviation of fitted splines of 3rd and 4th degrees diverge, so they are not appropriate for this patient. The higher degree splines (6th, 7th, 8th) define a good dental arch of the patient. The best fitting of the curve are obtained with the use of 6th degrees spline (10th control – K10): the maximum deviation is 0.219 mm at the left incisor, and the average deviation is 0.091 mm. The obtained value of the average deviation is smaller than the accuracy of the used scanner 23. Such a very small value of the average and maximum deviation of the fitted spline for dental arch curve is also a clear indicator that the treatment is reaching its completion.

Conclusion

The presented research enable us to define the following conclusions: comparison of dental arch curves is only possible if the jaw coordinate system adjusting was provided with precision and repeatability, and the convergence of the maximum and average deviation of the fitted splines are the criteria for selecting appropriate curve degree. The scanner resolution of at least 0.1 mm and accuracy of 0.2 mm is mathematical convergence criteria.

Described method opens new possibilities of using the digital dental modeling in orthodontic treatment and eliminates a subjective factor as well as make it possible to define the concept of personal orthodontics. Future research into this subject will be conducted by testing this approach in a new clinical study.

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