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A Quantitative Approach to Predict Ageing in Midsagittal Facial Profile

Ashraf Ibrahim Shaweesh[1,2,3], John Gerald Clement[3]

[1]Faculty of Dentistry, Jordan University of Science and Technology, Ramtha, 22110, Irbid, Jordan
[2]School of Dentistry and Health Sciences, Faculty of Science, Charles Sturt University, Wagga Wagga, New South Wales, Australia
[3]Melbourne Dental School, The University of Melbourne, Melbourne, Australia.

ABSTRACT

The aim of the present study was to introduce a quantitative method using Fourier analysis to predict ageing in midsagittal facial profile. Midsagittal facial profiles were extracted as lists of X-Y coordinates from 125 pairs of 3D facial scans captured at an average of 10.5 years apart for adult Japanese males aged 23–52 years. Coordinate files were categorized into three 10-year-long age groups and underwent Fourier analysis. In a test set of 10 individuals randomly selected from each age group, the predicted Fourier coefficients were calculated for each of the tested individuals using a leave-one-out linear regression analysis at each harmonic level. This was accomplished by the regression of the post-ageing coefficients onto their corresponding pre ageing coefficients. The accuracy of the predicted ageing coefficients were tested as the sum of squared errors between predicted and the actual post ageing coefficients ($SSE_{Pre\ ageing\ vs.\ Post\ ageing}$) in contrast to the errors between the pre and post ageing coefficients ($SSE_{Post\ ageing\ vs.\ Predicted\ ageing}$) using a paired t-test (α=0.05) across all tested individuals. Paired t-test showed that $SSE_{Pre\ ageing\ vs.\ Post\ ageing}$ were significantly larger than $SSE_{Post\ ageing\ vs.\ Predicted\ ageing}$ ($p = 0.034$) indicating that the coefficients of the predicted ageing are significantly closer to their corresponding actual post ageing coefficients than to the pre ageing coefficients. By using Fourier analysis, a quantitative prediction model for ageing in the midsagittal facial profile was introduced with some statistically supported accuracy. It is anticipated that testing the model further on other parasagittal and transverse facial contours and on younger and older age groups may open the door to possible applications in various disciplines of forensic science and clinical medicine.

Key words: *Fourier analysis; Harmonics; Facial profile; Quantitative analysis; Prediction Model; Ageing; Forensic Science.*

Introduction

Pre-existing photographic records of the face are necessary sources for the identification process. However, recent photographic reference records captured at the time of investigation are not always available. In such situations, the investigator is challenged by predicting how the face of a person under investigation would look like after some period of time. With the recent development of 3D imaging technology, there have been successful attempts to quantify and predict changes in facial topography induced by growth[1] and ageing[2].

The process of facial identification is often challenged further by the lack of direct frontal views, e.g. where surveillance footage only shows a lateral view of the face. Moreover, the only facial identity records available at many dental practices are lateral cephalograms which only show the soft-tissue profile of the face. Therefore, analysis of facial profile can be also important to the identification process.

Various methods exist for quantifying the facial profile. While direct anthropometric parameters such as angles and measurements were used in some studies[3–5], others used more advanced mathematical methods such as Procrustes superimposition/principal component analysis[6] and Fourier analysis[7–13].

Fourier shape analysis decomposes contours or curvatures into harmonic functions defined by Fourier descriptors[14]. Fourier shape analysis is a mathematical method based on converting a curved outline such as the midsagittal profile of the face into an infinite successive sine and

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cosine functions amenable to quantitative statistical description, comparison and analyses[15]. Fourier analysis has been used to quantify human facial profiles[8–10,12,13,16,17]. Most of the articles that employed Fourier analysis in studying longitudinal changes in facial profile focused on changes occurring during growth and development[8,16,18]. Studies using Fourier analysis to quantify age-related changes in adulthood have been very limited[9,11]. Ferrario et al.[9] used Fourier harmonic analysis to quantify and longitudinally evaluate the facial profiles of 14 adult subjects after 10 years. They computed the areas enclosed in each facial outlines and measured the difference in the area between pre and post ageing profiles. Ferrario et al.[9] reported significant age-related changes in facial profile in men and women. On the other hand, Kapur et al.[11] used lateral cephalograms of 77 subjects to extract the facial profiles. They then applied Fourier analysis to measure age-related longitudinal changes over a nine-year interval.

The use of Fourier analysis in the prediction of facial profile is evident in the work of Rose et al.[19] who introduced a prediction model based on relating hard-tissue cephalometric measurements with the Fourier coefficients of the soft-tissue profile. Rose et al. tested their model through correlating actual and predicted harmonics.

Other works employed different quantitative and statistical approaches to predict the soft-tissue facial profile. In a very recent study, Rupperti et al.[20] used a bivariate linear regression analysis to predict soft-tissue changes in facial profile following surgical movement of underlying bony structures. Similarly, Mala et al.[21] recently employed principal component analysis and multiple linear regressions to study the association between the soft tissue facial profile and the underlying hard-tissue structure and to determine the extent to which it might be possible to predict the former from the latter.

None of the aforementioned studies, and to the best of our knowledge, none of relevant studies in the literature, have actually employed Fourier analysis or any similar mathematical/statistical method in an attempt to predict ageing in soft-tissue midsagittal facial profile. The aim of the present study was to introduce and test a quantitative method using Fourier analysis to predict ageing in midsagittal facial profile. It is anticipated that the prediction model proposed by the present study may serve as the first building block for possible future applications in forensic sciences, orthodontics and orthognathic and plastic surgery.

Material and Methods

The present study is based on a joint collaboration between Melbourne Dental School (MDS) in Australia and the National Research Institute of Police Science (NRIPS) in Japan. Based on the collaboration, MDS burrowed from NRIPS a cohort of 688 three-dimensional facial scans of Japanese young and middle aged adults. The 3D scans had been acquired as part of an ongoing NRIPS research project titled "Ongoing research into improving the system for predicting age-related change in facial images (2016–2036)", which previously received the ethics approval from NRIPS Ethics Review Board. All participants had explicitly provided informed consent and consented to the sharing of their images with other collaborative research groups apart from the NRIPS team. Additionally, an approval from the Human Research Ethics Committee (HEAG) through the MDS Human Research Ethics Advisory Group (MDS-HREAG) (ID # 1646905) was granted under a project titled "3D quantification of age-related changes in facial morphology". The recently published first work out of the project was concerned with the quantification of the age-related changes in the facial profile.[22] The current work shares with the first published work the part related to the extraction of midsagittal profiles and their Fourier analyses, as detailed below.

Of the 688 facial scans, a sample of 125 paired scans of Japanese males captured at an average of 10.5 years apart was used for the present study. The baseline age of males ranged from 23–52 years. The scans were captured at baseline (pre ageing) between 1999 and 2004, and for each of the 125 subjects, the second scan was obtained between 2011 and 2014 (post ageing), with an average span of 10.5 ± SD of 1.5 years between the dates of capture of the two scans. The average age of participants at baseline was 35.6 years while the post ageing average age was 46 years. At baseline, the subjects were divided into three age groups; the younger / 3rd decade group (20–29 years; 33 subjects), the middle / 4th decade group (30–39 years; 54 subjects) and the older / 5th decade onwards group (40–52 years, 38 subjects).

The 3D facial scans were captured by NRIPS using an NEC stereophotographic scanner (Fiore) and saved as .nrf data files. All the scans were captured in the rest position. None of the subjects had undergone any facial surgery or been subjected to any form of trauma or malformation between the two scans that would have affected the shape of the facial profile. None of the baseline scans showed severely convex or concave facial profiles (reflecting an underlying skeletal malocclusion), facial hair or excessive facial fat (obesity).

All images were cleaned to include only the facial shell excluding hair. The midsagittal plane for each image was extracted using an automatic protocol[23]. In brief, all points of intersection between the midsagittal plane and the image were calculated starting from the soft-tissue glabella and ending at the soft-tissue menton. The points were coded in an arbitrary 2D coordinate system on the plane, sorted in clockwise order and the contour was closed via 'doubling'. The result was a list of 2D coordinates defining a closed contour, outlining the shape from the glabella to the menton and back to the glabella, which were written to a .csv file. This process employed multiple in-house software developed by Peter Claes[23] and a PhD candidate at Murdoch Children's Research Institute, Victoria, Australia.

Elliptical Fourier analysis quantifies a closed contour as two Fourier series. The curves of the x and y coordinates, as functions of their position on the closed contour, are each decomposed into a separate Fourier series which presents each curve as a series of coefficients on sine and cosine terms of increasing frequency. Each frequency level (harmonic) is represented by four coefficients A, B. C and D. The letters A and B denote the amplitudes of the cosine and sine terms modelling the change in the x-coordinate (or frontal projection), and the letters C and D denote the amplitudes of the terms modelling the change in the y coordinate (or vertex projection). The unique shape of any closed contour can be represented by these coefficients over different harmonic levels. Adding more harmonics increases the level of detail that is represented. When open contours, such as the facial profile, have been closed by 'doubling' only coefficients A and C are valid and B and D are zero.

Several authors have suggested that the midsagittal profile is reconstructed in adequate detail from the first 21 harmonics (including the orientation Harmonic 0)[4,12,13,22]. Therefore, in the present study, each contour was decomposed into the first 21 harmonics of each Fourier series (upon truncating Fourier series at the 20^{th} Harmonic level) using the in-house software "Fourier Shape Descriptor" (FSD) (developed at MDS by C.D.L. Thomas[24]. The first two harmonics (H0 and H1) are not descriptive of shape but describe orientation and size respectively. Gross shape starts to be represented by H2. Truncation of Fourier series at the 20^{th} harmonic, provided one orientation harmonic H0, one size harmonic H1 and 19 shape-specific harmonics (H2–H20)[22]. The midsagittal profile contours were normalised for remove the effect of orientation, position and size. Since coefficients B and D become zero in analysis of closed contours (contours closed by doubling), each profile was represented by two coefficients (A and C) at 21 harmonics.

Since coefficients A and C across the subjects at each harmonic level were normally distributed (using Kolmogorov-Smirnov and Shapiro-Wilk tests in SPSS version 24), linear regression analysis (SPSS version 24) of the post ageing onto the pre ageing (baseline) coefficients was run across all subjects at each harmonic level for each coefficient A and C, per age group. As a result, there were two linear regression equations (for coefficients A and C separately) at each harmonic, per age group. The format of the linear regression equations was:

$$y = bx + a$$

where b is the regression line slope (beta) and a is the intercept (or constant, the value of y when x = 0), x is a pre ageing coefficient and y is a post ageing coefficient.

These equations form the basis for predicting how a facial profile of an individual with a known ethnicity (e.g. Japanese), gender (e.g. male) and adult age group would look like in 10- year time. As b and a have been calculated for each age group from the actual pre ageing and the actual post aging coefficients, (the regression equation can be used to predict a post ageing acoefficient for any individual with a known pre ageing coefficient). When all of the predicted coefficients A and C across all the harmonic levels for an individual have been calculated,are given, they can be imported back to the FSD software to reconstruct their predicted post ageing profile.

To test for the accuracy of the proposed prediction model, in a set of 10 individuals randomly selected from each age group, the predicted Fourier coefficients were calculated for each of the tested individuals using a leave-one-out bivariate linear regression analysis at each harmonic level. This was accomplished by regressing the post-ageing coefficients onto their corresponding pre ageing coefficients. For the prediction model to be of value that the errors between the actual and predicted post ageing coefficients should be lower than the errors between the pre and the post ageing coefficients, which indicates that the predicted post ageing profile should be more similar to the actual post ageing profile that to the pre ageing profile. In this concept, the accuracy of the predicted post ageing coefficients was tested through calculating the sum of squared errors between the predicted and the actual post ageing coefficients ($SSE_{\text{post ageing vs. predicted ageing}}$) in contrast to the errors between the pre and post ageing coefficients ($SSE_{\text{pre ageing vs. post ageing}}$) using a paired t-test (α=0.05) across all tested individuals.

A one-way ANOVA test was used to show any differences between across the 3 age groups in terms $SSE_{\text{post ageing vs. predicted ageing}}$ against $SSE_{\text{pre ageing vs. post ageing}}$.

Moreover, to demonstrate the future use of the prediction model practically, the predicted Fourier coefficients of 10 of the tested cases (3 in the young age group, 4 in the middle age group and 3 in the old age group) were reconstructed using the FSD software and the resulted X and Y coordinates were used to plot the reconstructed facial profiles, which can be assessed visually against the corresponding original pre and post ageing profiles. The glabella point was used as a reference landmark to superimpose the reconstructed profiles.

Results

Table 1 and Figure 1 compare sums of squared errors (SSE) for the pre vs. post ageing coefficients against the errors for the post vs. predicted ageing coefficients for the 30 tested cases. The paired t-test across the 30 test cases yielded a statistically significant difference between $SSE_{\text{pre ageing vs. post ageing}}$ and $SSE_{\text{Post ageing vs. Predicted ageing}}$ ($t = 2.217$, $df = 29$, p=0.034 (α=0.05)). The mean difference in SSE was positive (1.4132), which indicates that the coefficients of the predicted ageing are significantly closer to their corresponding actual post ageing coefficients than to the pre ageing coefficients.

Although it is obvious in Table 1 that there are only 3 subjects with $SEE_{\text{pre ageing vs. post ageing}}$ smaller than $SEE_{\text{post ageing vs. predicted ageing}}$ in the older age group compared to 5 subjects in each of the other younger age groups, the one-way ANOVA test showed no statistically significant differences between the 3 age groups in terms of the differ-

TABLE 1

THE SUMS OF SQUARED ERRORS OF THE PRE VS. POST AGEING COEFFICIENTS AND OF THE POST AGEING VS. THE PREDICTED COEFFICIETS FOR THE 30 TESTING CASES

Test case	SSE Pre vs. Post	SSE Post vs. Predicted	Difference	Stat. Sig. α=0.05
G1_1	4.617	3.523	1.094	Paired t-test
G1_2	4.076	5.507	–1.431	$p = 0.035$*
G1_3	3.169	2.163	1.006	
G1_4	10.035	3.301	6.734	
G1_5	3.351	4.668	–1.317	
G1_6	12.475	5.962	6.513	
G1_7	0.341	1.699	–1.358	
G1_8	1.254	1.518	–0.264	
G1_9	8.673	5.220	3.453	
G1_10	5.302	7.467	–2.165	
G2_1	1.321	2.263	–0.942	
G2_2	0.748	0.552	0.196	
G2_3	34.977	19.713	15.264	
G2_4	3.690	1.814	1.876	
G2_5	4.062	4.471	–0.409	
G2_6	2.125	1.947	0.178	
G2_7	1.574	1.818	–0.244	
G2_8	2.457	2.976	–0.519	
G2_9	4.713	3.054	1.659	
G2_10	8.180	8.874	–0.694	
G3_1	2.759	2.097	0.662	
G3_2	3.473	0.781	2.692	
G3_3	12.046	6.773	5.273	
G3_4	4.150	2.060	2.090	
G3_5	0.458	2.109	–1.651	
G3_6	2.092	2.794	–0.702	
G3_7	5.101	1.718	3.383	
G3_8	2.813	4.006	–1.193	
G3_9	2.746	1.331	1.415	
G3_10	3.393	1.448	1.945	
Mean	5.206	3.788	1.418	

G1 – Group 1 (young / 3rd decade age group, G2 – Group 2 (middle / 4th decade age group, G3 – Group 3 (Old / 5th decade onwards age group.

ence in SSE between pre ageing vs. post ageing and post ageing vs. predicted ageing.

Figures 2, 3 and 4 show degree of fit between the reconstructed predicted and actual post ageing profiles for 10 of the tested cases. This is contrasted to the fit between the corresponding pre and post ageing profiles plotted alongside them. Predicted ageing profiles were fitted to actual post ageing profiles with a high degree of accuracy in eight out of the ten selected cases.

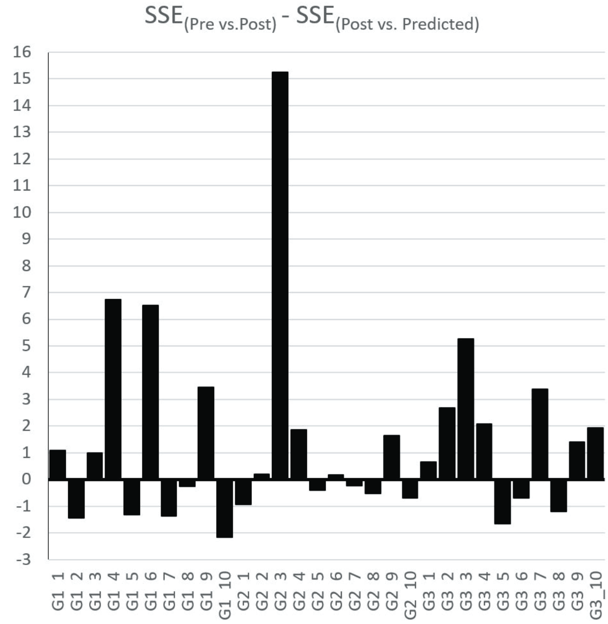

Fig. 1. A bar graph plotting the differences in the sums of squared errors between the pre vs. post ageing and the post s. predicted ageing coefficents for each individual in the test set. G1 – Group 1 (young / 3rd decade age group, G2 – Group 2 (middle / 4th decade age group, G3 – Group 3 (Old / 5th decade onwards age group.

Discussion and Conclusion

Previous approaches to mathematical description of facial profile described the facial profiles in terms of distances and angles and focused on size and angular differences[3–5]. Fourier analysis not only has the capacity to quantify size differences[24,25] but also allows shape quantification. Although shape differences between two profiles may be studied qualitatively by superimposition and direct visual assessment, quantifying form (size and shape) using a mathematical approach such as Fourier analysis allows converting shape curvatures into sine and cosine coefficients amenable to more objective comparisons using simple statistical tests such as correlation tests and t-tests. Moreover, a bivariate linear regression model can be fit to quantify and predict shape differences between two profiles. This may help establish a building block for possible applications in forensic facial identification, forensic facial approximation, orthognathic surgery, plastic surgeries and surgical facial shape rejuvenation.

The current study introduced a model of predicting the shape of the soft-tissue profile longitudinally over a 10.5 year interval using Fourier analysis. In a similar Fourier analysis-based concept, Rose et al.[19] reported a model based on multi-variate relationship between 11 hard-tissue cephalometric measurements and the Fourier coefficients of the soft-tissue profile, which generated 50 predicted x and y harmonic coefficients. Rose et al.[19] tested their model through correlating actual and predicted har-

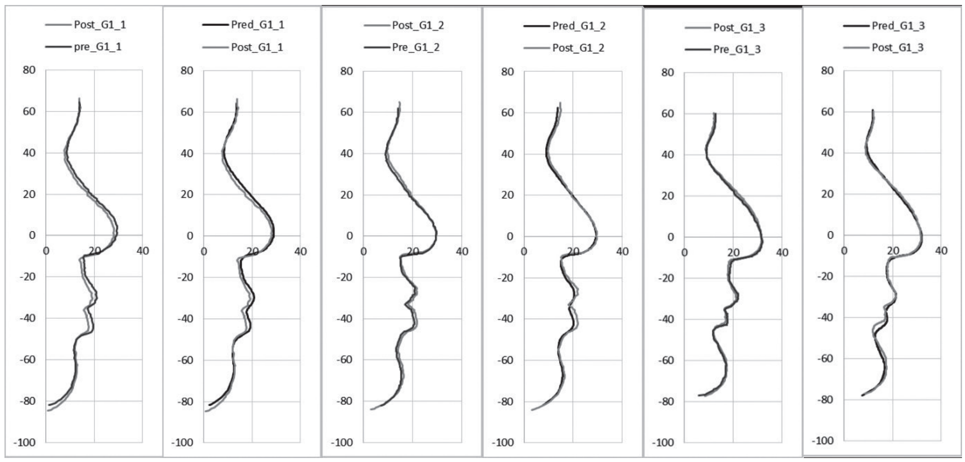

Fig. 2. Predicted post ageing profiles (pred) for 3 cases in age group 1 superimposed to the corresponding actual post ageing profile (post). The degree of fit is assessed in contrast to the fit between the pre ageing (pre) and post ageing profiles.

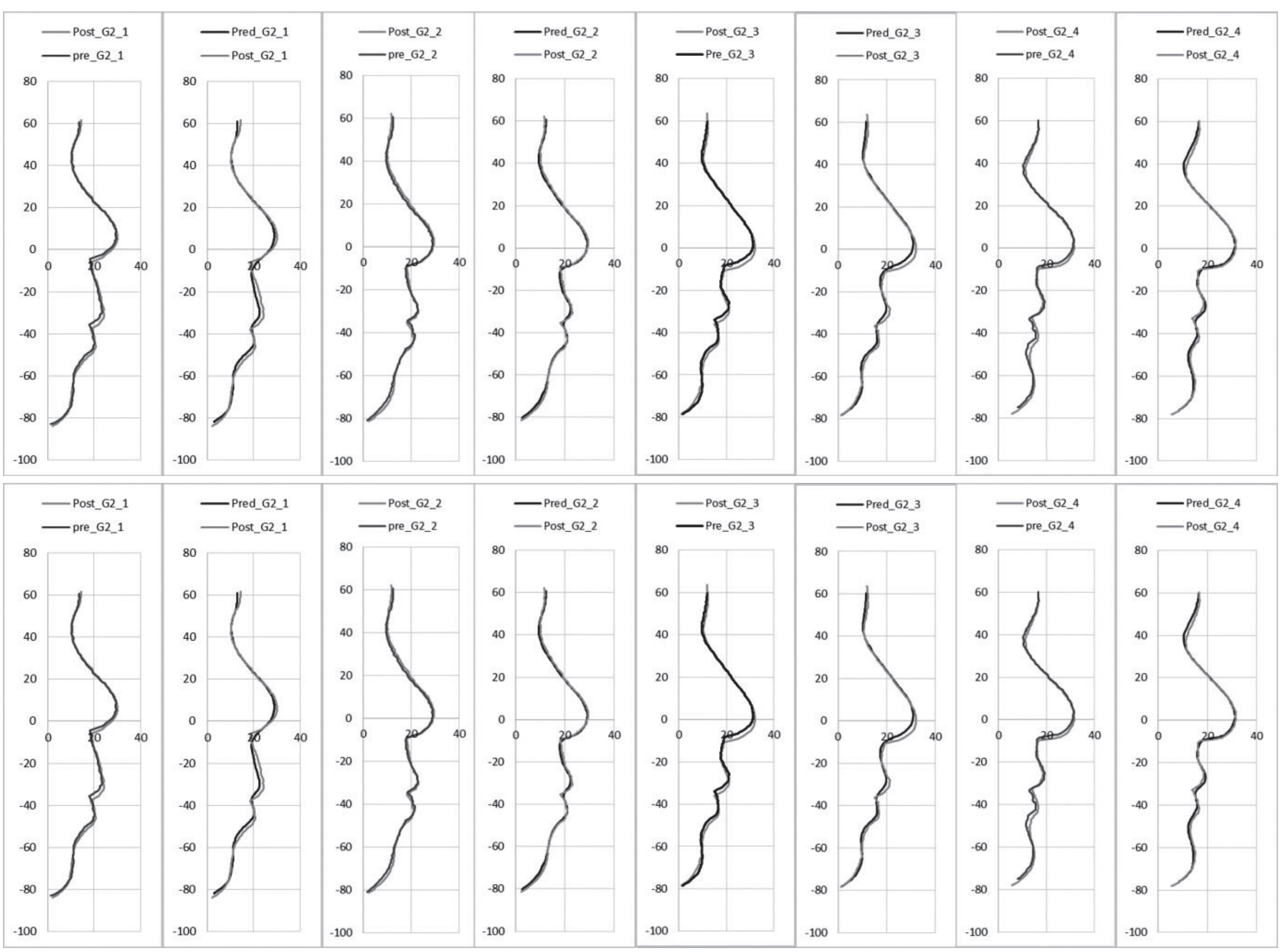

Fig. 3. Predicted post ageing profiles (pred) for 4 cases in age group 2 superimposed to the corresponding actual post ageing profile (post). The degree of fit is assessed in contrast to the fit between the pre ageing (pre) and post ageing profiles.

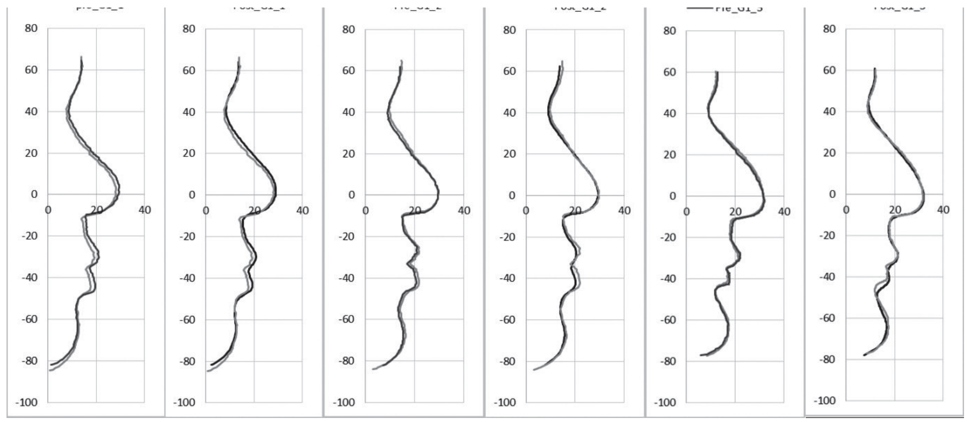

Fig. 4. Predicted post ageing profiles (pred) for 3 cases in age group 3 superimposed to the corresponding actual post ageing profile (post). The degree of fit is assessed in contrast to the fit between the pre ageing (pre) and post ageing profiles.

monics. Their correlation tests revealed strong relationships for many of lower order harmonics that describe the gross shape of the facial profile. However, higher order harmonics that produce the detailed shape of the profile did not show strong correlations with the cephalometric measurements, which limited the use of Rose et al.'s model only to forensic facial reconstruction with questionable applicability to clinical diagnosis and planning.

Rose et al.'s approach differed from ours in terms of the purpose, the predicting variables and the testing method. The purpose of Rose et al.'s model was to predict the shape of soft-tissue profile irrespective of the effect of ageing while we aimed at using the model to predict the shape of the ageing facial profile longitudinally. Rose et al. used cephalometric measurements to predict the facial profile Fourier coefficients. In contrast, we used linear regression analyses to predict the post ageing profile harmonics from the linear relationship between the pre and the actual post ageing profile harmonics. Lastly, Rose et al. used correlation analysis to test for the fit between the actual and predicted coefficients. In contrast, we tested the accuracy of our model with reference to the pre-ageing coefficients (through the difference in SSE between two pairs of variables, pre vs. post ageing coefficients and post ageing vs. predicted coefficients).

In the statistical testing of the accuracy of the prediction model, the differences between $SSE_{\text{pre vs. post}}$ and $SSE_{\text{post vs. predicted}}$ were found statistically significant. The greater $SSE_{\text{pre vs. post}}$ than $SSE_{\text{post vs. predicted}}$ in general, the positive mean difference and the statistical significance of the difference indicate that the coefficients of the predicted ageing were significantly closer to their corresponding actual post ageing coefficients than to their corresponding pre ageing coefficients. This reflects that the proposed model can be of some value especially in the older age group. Nevertheless, the model needs to be tested further on other parasagittal and transverse profiles and on other curved facial outlines before it may find possible applications in forensic sciences and clinical and surgical medicine.

Kapur et al.[11] and Shaweesh et al.[22] reported age-related changes in midsagittal facial features within 1 mm at a 10-year interval. This may explain why the reconstructed predicted facial profile in 2 of the demonstrated cases (Figure 2, G1_2 and Figure 3, G2_1), were not close enough to fit the actual post-ageing profile. As age-related changes in facial topography are more evident in the elderly (induced by loss of volume, skin atrophy, ageing nasal changes, tooth loss, tooth wear and loss in the vertical dimension of occlusion), testing the proposed prediction model on these age categories in the future may help reflect better clinical/forensic relevance.

Facial profiles were extracted from 3D photographic scans and readily exported as x-y .csv files. In many of the previous similar studies[11–13, 19] facial profiles were extracted by manually tracing 2D photographic images or cephalograms, which is more demanding, time consuming and likely subject to a greater operator error. Three-dimensional scans could also be used to extract and analyse age-related changes in other parasagittal and transverse profiles. When quantitative analyses of midsagittal, parasagittal and transverse profiles become possible, this would provide prediction of ageing at more topographic sections of the face.

Since paired scans for females were still unavailable, only scans of male subjects were used in the present study. However, as this approach proved some accuracy for prediction of ageing in facial profile on male scans, the same method can be applied on female scans in the future to see if a sexual dimorphism exists in the capacity of Fourier analysis to predict ageing in facial profiles. In a similar way, the reliable application of the proposed method on Japanese scans is a prompt for applying it on people of other ethnic backgrounds to investigate inter-ethnic variations. In this regard, Sheridan et al.[12] studied inter-ethnic quantitative differences in facial profile two decades ago, however, their cross-sectional approach study did not consider quantifying age-related changes in the facial profile.

In conclusion, using Fourier analysis, a quantitative prediction model for ageing in the midsagittal facial profile was introduced with some statistically supported accuracy. Testing the model further on other parasagittal and transverse facial contours and on younger and older age groups may open the door to possible applications in various disciplines of forensic science and clinical medicine.

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Declaration of Interests

The authors report no conflict of interests

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A. I. Shaweesh

Faculty of Dentistry, Jordan University of Science and Technology, Ramtha, 22110, Irbid, Jordan
E-mail: ashrafis@just.edu.jo

KVANTITATIVNI PRISTUP U PREDVIĐANJU STARENJA NA MIDSAGITALNOM PRIKAZU LICA

SAŽETAK

Cilj ovog istraživanja bio je primijeniti kvantitativnu metodu pomoću Fourierove analize za predikciju starenja na uzdužnom (midsagitalnom) prikazu lica. Uzdužni prikazi lica su ekstrahirani kao popisi X-Y koordinata za 125 parova 3D skeniranih lica snimljenih u prosjeku u razmaku od 10,5 godina u odraslih japanskih muškaraca u dobi od 23-52 godine. Datoteke koordinata kategorizirane su u tri starosne skupine od 10 godina i podvrgnute Fourierovoj analizi. Za 10 pojedinaca nasumično odabranih iz svake dobne skupine, predviđeni Fourierovi koeficijenti izračunati su za svakog od tih pojedinaca korištenjem linearne regresijske analize tehnikom poprečne validacije ispuštanjem po jedne vrijednosti motrenja na svakoj harmonijskoj razini. To je postignuto regresijom odgovarajućih koeficijenata poslije-starenja na koeficijente prije-starenja. Točnost predviđenih koeficijenata starenja ispitana je kao zbroj kvadrata pogrešaka između predviđenih i stvarnih koeficijenata poslije-starenja (SSE prije starenja vs. poslije starenja), za razliku od pogrešaka između koeficijenata prije i nakon starenja (SSE poslije-starenja vs. predviđeno starenje) pomoću uparenog t-testa (α = 0,05) u svim ispitivanim pojedincima. Upareni t-test pokazao je da je SSE prije starenja vs. poslije starenja bio značajno veći od SSE poslije-starenja vs. predviđeno starenje (p = 0,034) što ukazuje da su koeficijenti predviđenog starenja značajno bliži njihovim stvarnim koeficijentima poslije-starenja nego onima prije-starenja. Korištenjem Fourierove analize omogućen je kvantitativni model predikcije starenja na midsagitalnom prikazu lica uz određenu razinu statističke točnosti. Daljnje ispitivanje modela na sekvencijskim prikazima parasagitalne i transverzalne ravnine lica te na mlađim i starijim dobnim skupinama može otvoriti vrata za moguću primjenu u različitim disciplinama forenzičke znanosti i kliničke medicine.