Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Forensic Science International 150 (2005) 23–32
Forensic Science International
www.elsevier.com/locate/forsciint

Quantification of the shape of handwritten characters: a step to objective discrimination between writers based on the study of the capital character O

R. Marquis[a,*], M. Schmittbuhl[b], W.D. Mazzella[a], F. Taroni[a,c]

[a] *School of Criminal Sciences, BCH, University of Lausanne, CH-1015 Lausanne-Dorigny, Switzerland*
[b] *Team Research EA 3428, Dental Faculty, F-67085 Strasbourg, France*
[c] *Institute of Legal Medicine, University of Lausanne, CH-1005 Lausanne, Switzerland*

Received 12 January 2004; received in revised form 17 June 2004; accepted 17 June 2004
Available online 25 August 2004

Abstract

In view of contributing to the scientific validation of the individuality of handwriting, the testing of the two so called fundamental laws of handwriting—1: no two people write exactly alike; 2: no one person writes the same word exactly the same way twice—was approached by analysing the shape of 445 handwritten capital characters O produced by three individuals. A methodology based on classical Fourier descriptors was applied to the characters contours, which were extracted through an automated procedure of image analysis. Precise individual characterization of the shape was possible through Fourier analysis. Within-writer variability of the shape of character O for the writers selected could be shown in an objective and quantitative way through the statistical analysis of the Fourier descriptors. It was demonstrated that this polymorphism differed between the three writers. Differentiation between writers was quantitatively demonstrated by discriminant analysis of the Fourier descriptors, and by the existence of marked morphological distances between the set of characters O of each writer. The degree of dissimilitude of the character O writings could, thus, be assessed. Because of relatively reduced within-writer variability and a pronounced differentiation between the writers, a morphological profile could be established and discrimination between writers could be obtained through the quantification of the shape of one handwritten character.

Keywords: Handwriting; Variability; Shape analysis; Fourier descriptors

1. Introduction

The individualization of handwriting is largely dependent on analysis by examiners, who evaluate the characteristics of the writing in a qualitative or subjective way. Various articles [1–5] as well as the decision of United States versus Starzecpyzel [6] in 1995, citing Daubert versus Merrell Dow Pharmaceuticals, Inc. [7], have highlighted this lack of objectivity. Validity of the fundamental laws expressing the variability and the individuality of handwriting—1: no two people write exactly alike; 2: no one person writes the same word exactly the same way twice [8]—were questioned, challenging the reliability of the field of handwriting individualization. Various studies have already been undertaken to reduce or eliminate the subjective part of the handwriting analysis process: studies of classification [9–11], studies of frequencies of certain handwriting characteristics in given populations [12–18] and, more recently,

* Corresponding author. Tel.: +41 21 692 4600; fax: +41 21 692 4605.
E-mail address: raymond.marquis@esc.unil.ch (R. Marquis).

0379-0738/$ – see front matter
doi:10.1016/j.forsciint.2004.06.028

methods for identification of writers [19–23]. The main purpose of these methods is to partially automate the analysis process in order to support the examiner.

Letter shape has not been studied in a global and precise way within the various existing methods; only certain aspects of it have been approached by a variety of geometrical measurements. The theoretically high degree of variability of the shape of handwritten characters [24] as well as its very frequent use in the comparison of handwritings [25] indicate that it is a worthy characteristic to be subjected to statistical study.

In this research, Fourier descriptors were used to study the variability of the shape of the handwritten capital character O of three writers, in order to demonstrate a possible application of the proposed method. The character O was retained because it is one of the best examples of closed contours among handwritten characters.

2. Materials and methods

2.1. Sampling

The samples were collected from a text, written in French, which was copied twice per day during 15 days by fifteen collaborators of the School of Criminal Sciences of the University of Lausanne (Switzerland). The documents were written by means of ballpoint pens with black ink Bic® cristal™ medium on standard blank paper, Xerox® Business™ Laser/Copier/Inkjet, 80g/m^2, of A4 format. In particular, the text included the capital character O sixteen times, both within various combinations of characters in words as well as in isolation.

In order to validate the analysis method, three writers (W1, W2 and W3) were selected among the fifteen individuals of the sample, based on a visually perceptible difference between the shapes of their characters O (Fig. 1). Only the characters O that were closed and not superimposed with other characters were used. In total 445 characters were analysed, 144 written by W1, 171 by W2 and 130 by W3.

2.2. Image analysis procedure

The documents were digitized by means of an Imacon® Flextight 2848™ scanner, with a resolution of 1500 ppi. The images of characters obtained were treated by means of the image analysis software Visilog® Xpert 6.11 (Noesis). Firstly, a threshold was applied to binarize the images. Then, the contours were extracted by skeletonizing the images. Finally, the contours were expressed in polar coordinates. Each contour could therefore be described by a discrete function $R(\theta)$, representing the length of a line joining a point of the contour to the centroid, θ being the angle made by this line with the horizontal axis. A total of 128 pairs of polar coordinates defined the contour of each handwritten character O. The stages of the image analysis procedure are illustrated in Fig. 2.

2.3. Size normalization

All the characters were normalized in size, since size is not relevant for the characterization of shape. For this operation, the coordinates of the outlines were recalculated in such a way that the enclosed areas were equal.

2.4. Fourier analysis

A shape analysis based on the classical Fourier methodology was performed on each contour. This analysis

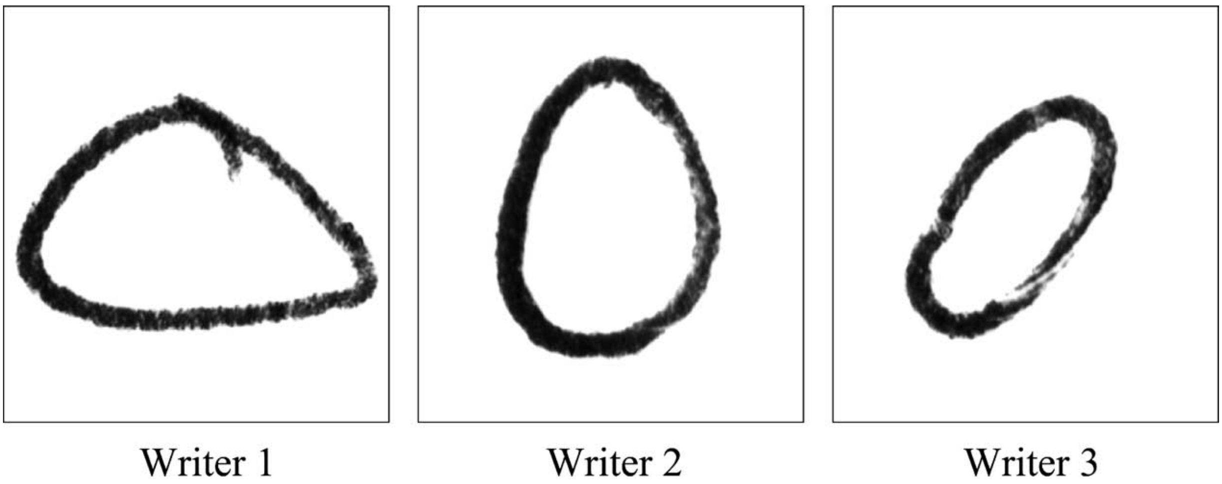

Fig. 1. Examples of handwritten capital characters O of the three selected writers W1, W2 and W3.

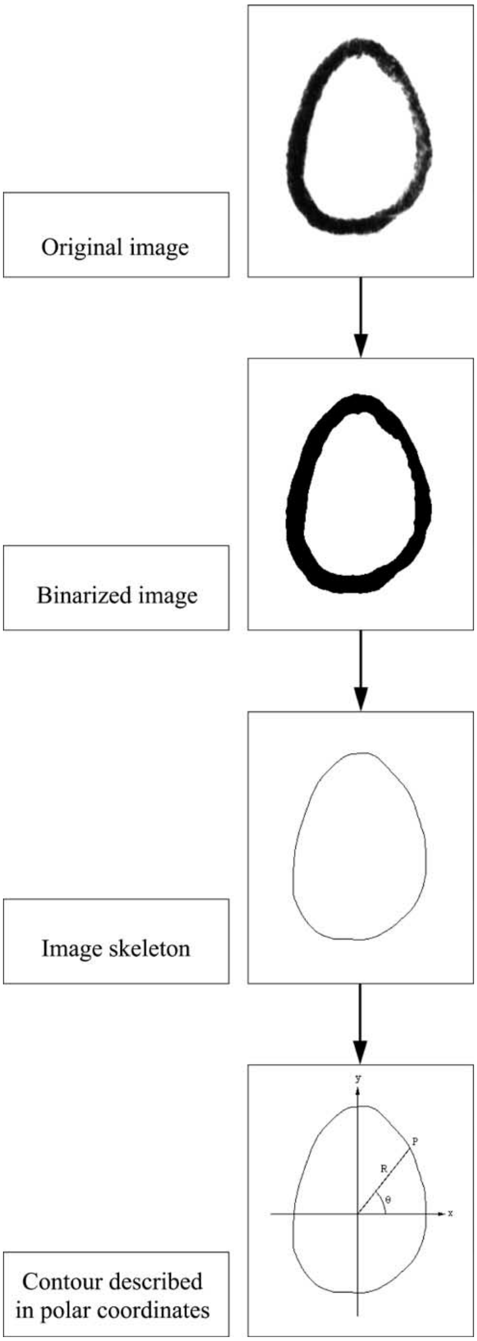

Fig. 2. Image analysis procedure for extraction of the contour of the handwritten character O. In the final stage of the procedure, each point P of the contour is described by a pair of polar coordinates: P (R, θ).

provides a morphological characterization of simple closed contours—any contour is simple if any radius departing of its centroid intercepts the periphery only once [26].

The Fourier series expansion of the discrete periodical function $R(\theta)$ describing a contour leads to the following mathematical expression [27]:

$$R(\theta) = A_0 + \sum_{j=1}^{n} [A_j \cos(j\theta + \theta_j)]$$

In this expression, the contour is characterized by a series of harmonics, each harmonic being defined by a frequency (j), an amplitude (A_j) and a phase (θ_j). The amplitude and the phase are called the Fourier descriptors. The amplitude of a harmonic represents the relative importance of its contribution to the original shape of the contour; the phase represents the orientation of the harmonic contribution.

The first harmonic is the ovate contribution to the shape, the second one describes its elliptic aspect and thus, informs about the elongation of the shape, the third one characterizes the triangularity of the shape, the fourth its quadrangularity, the fifth its pentagonality, the sixth its hexagonality [27,28].

Furthermore, the contour of each character O could be progressively reconstructed by summing the Fourier harmonics [28].

The present shape analysis was accomplished by using software developed by Schmittbuhl et al. (1998) [27].

2.5. Polar representations of the Fourier descriptors

A polar representation of the Fourier harmonics was constructed for all of the handwritten characters of each writer. In this representation, each Fourier harmonic corresponds to a point for which the radial coordinate is the Fourier amplitude and the angular coordinate is the Fourier phase. Thus, for each writer and for each harmonic, a cloud of points was obtained, where each point corresponded to one handwritten character.

2.6. Statistical analysis

The numerical data obtained was treated statistically using the S-plus® 2000 software (Mathsoft Inc.). For each writer, the average and the standard deviation were calculated for each pair of Fourier descriptors. The pairs of Fourier descriptors of the harmonic of order 0 were excluded from the analysis because they only contain information about the size of the object, which was standardized.

A canonical discriminant analysis was performed on the pairs of Fourier descriptors. For each analysed contour, the result of this multivariate analysis was represented on a two-dimensional scatter-plot defined by the first and second discriminant axes. The correlation of each variable with each discriminant axis was calculated. In order to estimate the within-writer variability, Euclidean distances were calculated between all possible pairs of characters. For each pair of characters, this distance was calculated from the standardized Fourier descriptors of each handwritten character. Then, the mean Euclidean distance and the standard deviation were determined for each writer. In order to express the between-writer variability, Mahalanobis distances between each pair of groups—a group corresponding to the set of characters of each writer—were calculated. Then, the Hotelling's T Squared test was used to test differences in means between the three groups corresponding to the three writers. Finally, a cross-validation was applied to estimate the correct classification rate of the discriminant function. This is a leaving-one out method. A discriminant function was derived on the basis of N-1 of the contours and then used to classify the contour omitted; the process was then repeated for each contour in turn [29].

3. Results

The statistics of the Fourier descriptors (amplitudes and phases) of the handwritten character O skeletons of each writer are summarised in Tables 1 and 2. Since the first six Fourier harmonics provide reconstructed outlines very close to the original contours, only the first six pairs of descriptors were employed. Polar representations of the Fourier descriptors (Fig. 3), geometrical contributions of the Fourier harmonics (Fig. 4) and step-by-step reconstructions (Fig. 5) are illustrated for these six first harmonics.

3.1. Shape characterization and morphological differences of the contours

Precise characterization of the shape of each character O was possible with Fourier analysis. Each contour is described by a series of parameters (the Fourier descriptors); the precision of this characterization is confirmed by the quality of the step-by-step reconstructions of the contours with the use of the first six harmonics (Fig. 5).

An elliptical elongation, described by the second harmonic, was observed for the characters of each writer, as deduced from the high importance of amplitudes of the second Fourier harmonic compared to the values of amplitudes of the other harmonics (Table 1). This elongation was particularly marked for the third writer (see the 2nd harmonic in Figs. 3 and 4), which was characterized by a greater value of A_2 (2.09) than those of the characters of writers W1 and W2 (0.89 and 0.92, respectively). Furthermore, the mean orientation of the long axis of the corresponding contribution (θ_2) was almost horizontal for the handwritten characters of W1 (174.75°), indicating that these characters are quite flat, whereas the second harmonic of characters of W2 was oriented at 52.71° and that of W3 at 37.24° (Table 2), reflecting the right orientation of the characters of these two writers.

Table 1
Fourier analysis of the handwritten characters O contours of the writers W1, W2 and W3: summary statistics[a] of the first six Fourier amplitudes

Fourier amplitudes	Writer 1		Writer 2		Writer 3	
	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.
A_1	0.08	0.04	0.08	0.04	0.10	0.04
A_2	0.89	0.35	0.92	0.42	2.09	0.38
A_3	0.41	0.14	0.28	0.11	0.16	0.09
A_4	0.19	0.09	0.20	0.13	0.59	0.23
A_5	0.13	0.06	0.11	0.06	0.14	0.07
A_6	0.10	0.05	0.08	0.05	0.19	0.11

[a] $\overline{X}$, mean; S.D., standard deviation.

Table 2
Fourier analysis of the handwritten characters O contours of the writers W1, W2 and W3: summary statistics[a] of the first six Fourier phases[b]

Fourier phases	Writer 1		Writer 2		Writer 3	
	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.
θ_1	123.21	77.01	248.27	97.18	257.38	93.74
θ_2	174.75	19.48	77.92	17.76	37.24	10.89
θ_3	99.69	10.31	89.38	12.61	165.01	25.21
θ_4	85.37	12.61	77.35	13.75	127.77	12.03
θ_5	56.15	10.31	84.80	13.75	46.41	14.32
θ_6	44.96	10.29	25.70	14.10	36.31	14.56

[a] $\overline{X}$, mean; S.D., standard deviation.
[b] Phases are given in degrees.

The triangularity appeared to be more marked in group W1, as illustrated by the amplitude of the third Fourier harmonic for this group compared to that of the groups W2 and W3 (0.41 against 0.28 and 0.16, respectively) (see the 3rd harmonic in Figs. 3 and 4). In group W3, the contribution of the third harmonic is very weakly triangular (Fig. 4, third harmonic of the right column); the reduced importance of this harmonic is illustrated by the fact that there is practically no difference between the reconstructions of the original contours whether considering the first two or the first three Fourier harmonics (Fig. 5, right column). The mean orientation of the triangular contribution was not very different between writers W1 and W2, as supported by the phase angular values of the third Fourier harmonic (99.69° and 89.38°, respectively). These values show that the first leaf of the trefoil contribution to the original shape of characters O of W1 and W2 is nearly on a vertical axis. For the writer W3, the phase angular value of the third Fourier harmonic (165.01°) indicates that the first leaf of the trefoil contribution of writer W3 presents an orientation close to the horizontal axis (see the third harmonic in Fig. 3).

A relative quadrangularity of the characters O was observed principally in group W3, as demonstrated by the relative importance of the amplitude of the fourth harmonic for this writer (0.59) compared with this value in W1 and W2 (0.19 and 0.20, respectively). Contrary to what was observed in the two other groups, quadrangularity in group W3 is much more pronounced than triangularity. The orientation of the squared shape of characters of the third writer (W3) was

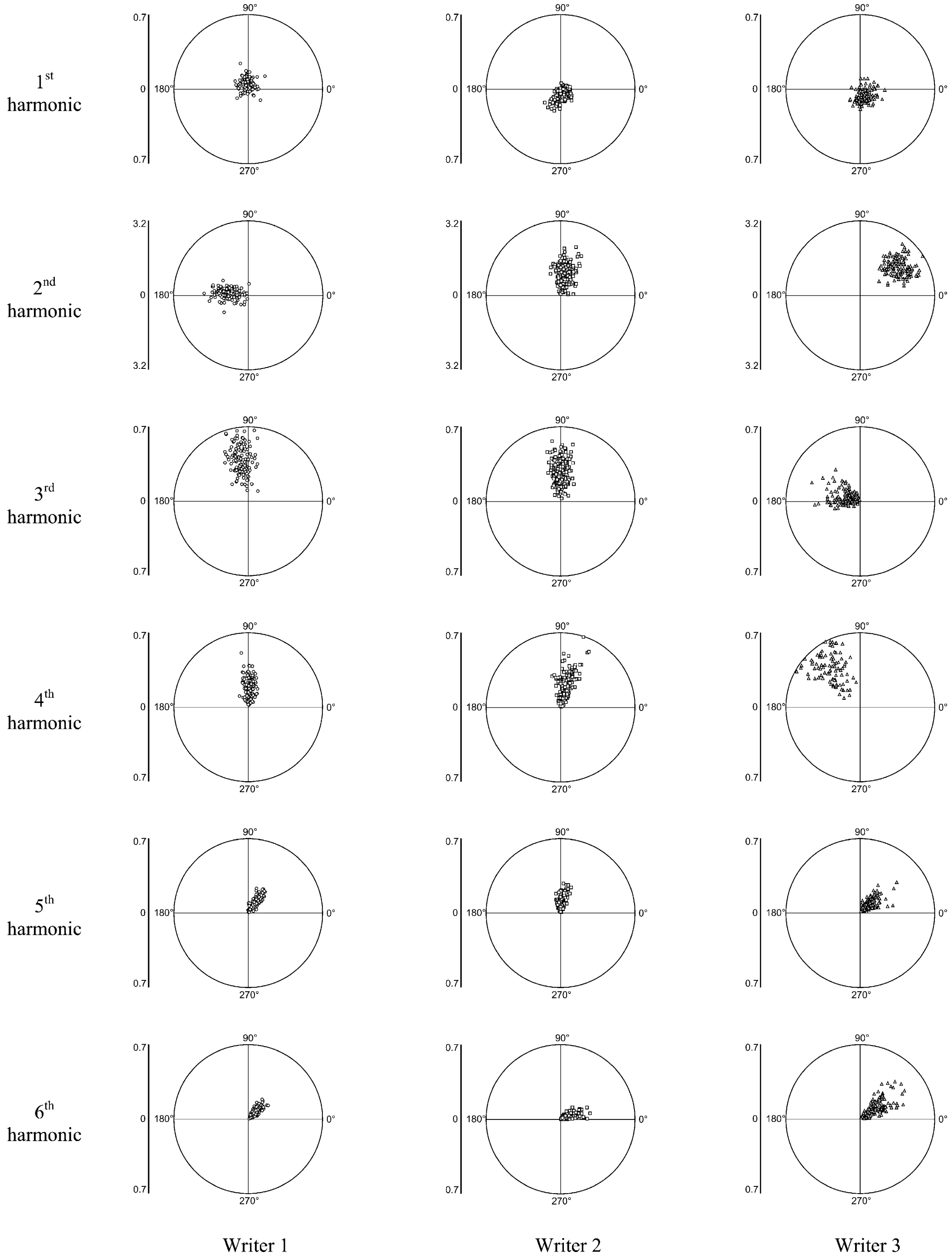

Fig. 3. Polar representations of the Fourier harmonics 1 to 6 of the handwritten characters O for each writer W1 (rounds), W2 (squares) and W3 (triangles). Amplitude scale, which is indicated for each polar representation, differs for the 2nd harmonic since its amplitude, for the three writers, are high compared to the other harmonics values (see Table 1).

distant from that of W1 and W2: 127.27° against 85.37° and 77.65°, respectively.

The pentagonality of the handwritten characters O was rather reduced and not very different for the three writers, as shown by the relatively low values of the amplitude of the fifth Fourier harmonic for these writers (0.13, 0.11 and 0.14, respectively). The orientation of the pentagonal shape in group W2 was significantly different from that of groups W1

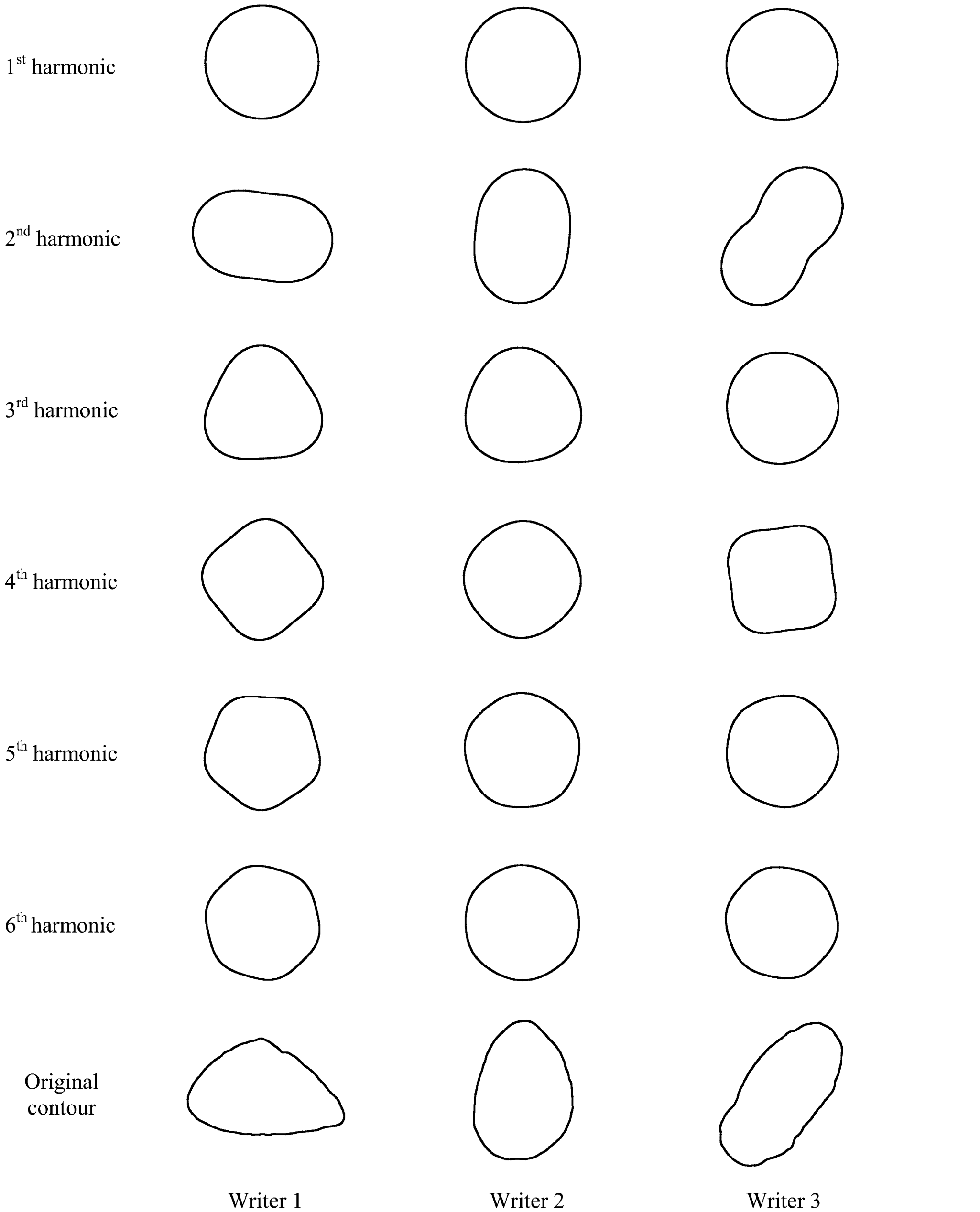

Fig. 4. Examples of illustrations of the geometrical contributions of the first six Fourier harmonics characterizing one character O skeleton of each writer.

and W3, as demonstrated by the phase angular values of the fifth Fourier harmonic: 84.50° against 56.15° and 46.41°, respectively.

Hexagonality was marked for the characters of the third writer (W3), as demonstrated by the value of the amplitude of the sixth Fourier harmonic (0.19), which is the third in importance for this writer. The contribution of the sixth harmonic is not so important in groups W1 and W2, as indicated by the corresponding amplitudes (0.10 and 0.08, respectively).

3.2. Variability of handwritten capital characters O

3.2.1. Within-writer variability

A polymorphism of the handwritten characters O was objectively shown for each of the three individuals of the

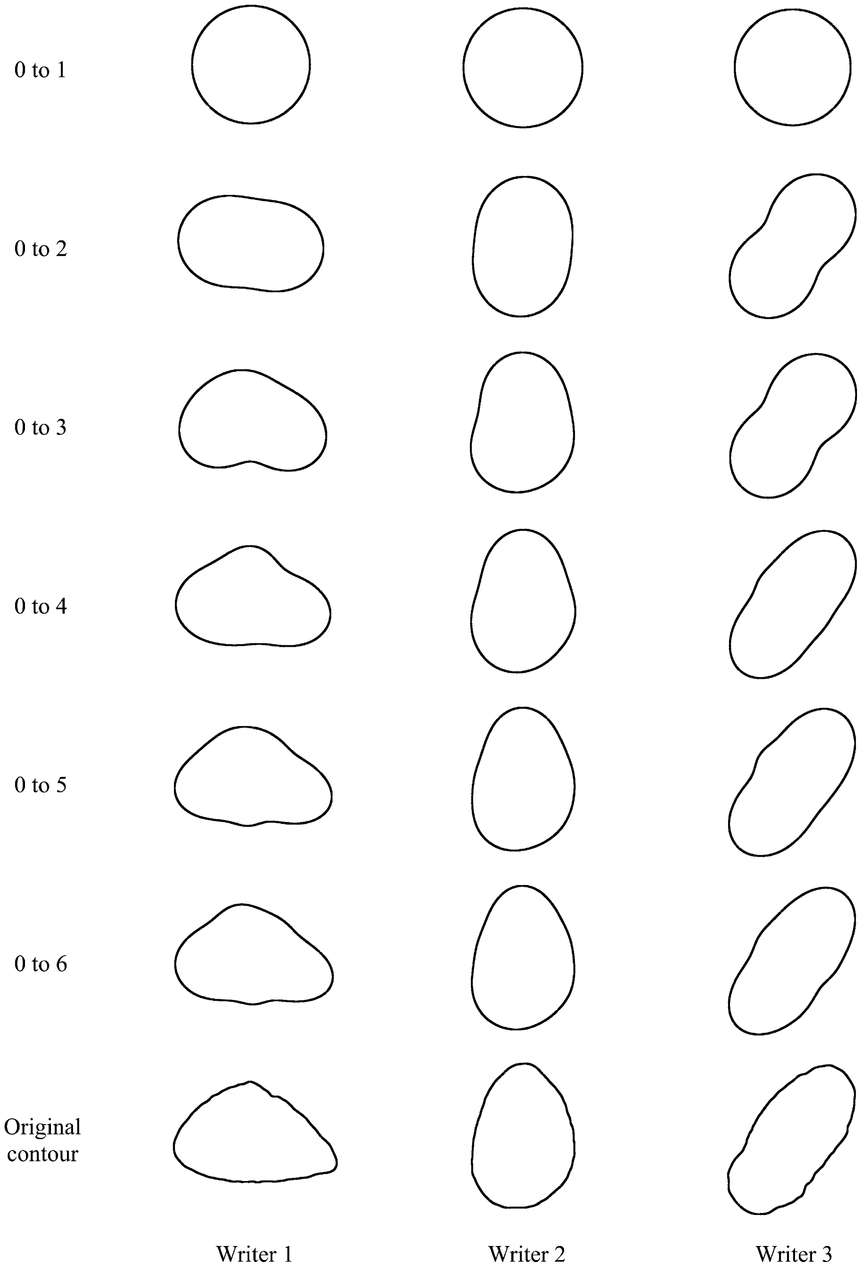

Fig. 5. Examples of step-by-step reconstructions of one character O skeleton of each writer, with an increasing number of harmonics, from 1 to 6.

study. The contours in group W3 presented a morphology that was more variable than in groups W1 and W2, as demonstrated by the greater value of the Euclidean distances mean in W3 compared to those in W1 and W2 (Table 3). Pair-wise comparisons showed significant differences in Euclidean distance means in each pair of writers at $P < 0.001$ (Wilcoxon Rank test).

3.2.2. Between-writer variability

The clouds of individual contours of each writer presented no overlapping, as shown by the canonical discriminant analysis for W1, W2 and W3 of the first six pairs of Fourier descriptors (Fig. 6). Allocation of each of the 445 studied contours to the writer with the closest centroid allowed for the correct classification of all the characters.

Table 3
Polymorphism in each of the writers, W1, W2 and W3, determined from the Fourier analysis of the handwritten characters O: Euclidean distances of all possible pairs of observations in each group, calculated from the standardized Fourier descriptors

Writer	Euclidean distances	
	$\overline{X}$[a]	S.D.[b]
W1	2.62	0.54
W2	3.02	0.49
W3	3.56	0.71

[a] $\overline{X}$, mean.
[b] S.D., standard deviation.

Table 4
Morphological differences between writers W1, W2 and W3 determined from the Fourier analysis of the handwritten characters O: Mahalanobis distances between each pair of groups[a]

Pair of writers	Mahalanobis distance
W1–W2	73.04
W1–W3	160.40
W2–W3	93.83

[a] All distances were significant at $P < 0.001$ (Hotteling's T Squared test).

The Mahalanobis distances between each pair of groups (Table 4) were calculated and, based on the Hotelling's T Squared test, the differences between multivariate mean values were highly significant ($P < 0.001$). Furthermore, the applied cross-validation assigned all characters but one to their respective writer. The first canonical discriminant function accounted for 71.1% of the total variance, while the second one explained the remaining 28.9%. The first canonical discriminant function contributed to the separation of each writer from the two others, whereas the second one separated writer W2 from W1 and W3 (Fig. 6). The first canonical discriminant function (Can1) was principally correlated with amplitudes A_2, A_4, and phases θ_2, θ_3, θ_4, and the second canonical discriminant function (Can2)

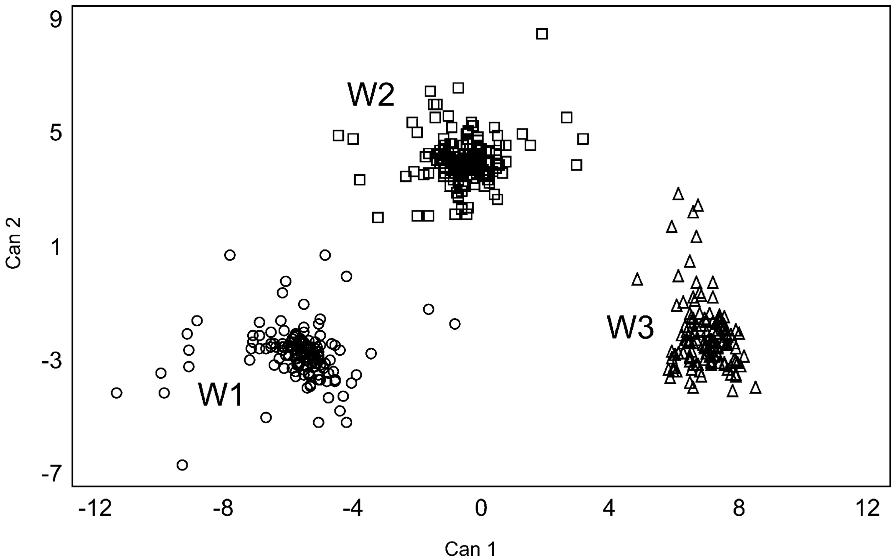

Fig. 6. Results of the canonical discriminant analysis performed on the first six pairs of Fourier descriptors (A_1–A_6, θ_1–θ_6) of the 445 handwritten characters O studied.

Table 5
Discriminant analysis of the six first pairs of Fourier descriptors of the handwritten characters O of the three writers W1, W2 and W3: correlation of Fourier descriptors with the first and the second discriminant functions

First canonical discriminant function				Second canonical discriminant function			
Fourier amplitudes	r[a]	Fourier phases	r	Fourier amplitudes	r	Fourier phases	r
A_1	0.04	θ_1	−0.11	A_1	−0.04	θ_1	−0.11
A_2	0.25	θ_2	−0.62	A_2	−0.17	θ_2	−0.36
A_3	−0.16	θ_3	0.32	A_3	0.02	θ_3	−0.33
A_4	0.20	θ_4	0.27	A_4	−0.14	θ_4	−0.30
A_5	0.01	θ_5	−0.06	A_5	−0.07	θ_5	0.39
A_6	0.10	θ_6	−0.05	A_6	−0.10	θ_6	−0.18

[a] r: correlation coefficient.

was mainly correlated with phases θ_2, θ_3, θ_4 and θ_5 (Table 5).

4. Discussion

The image analysis procedure presented here provides an objective way of extracting the contours of the handwritten capital character O since all the stages of the procedure, from the original image to the skeletonized curve, are automated. The skeleton was retained because it best represents the shape of the characters. It also reduces the influence of internal and external boundary irregularities of the shape, which are not relevant for describing the shape itself.

Fourier descriptors were chosen for the analysis of the shape of closed curves. This technique is already effective in a variety of scientific fields [27,28,30,31]. It permits the description of a shape as a whole; both global and local aspects of a contour are amenable to analysis [27]. The shape of the handwritten capital characters O was depicted precisely by using the Fourier descriptors. A direct representation of the geometrical contribution of the Fourier harmonics is possible, since each harmonic represents the *n*-leaves shape that takes part in the characterization of the original shape of a contour. This geometric interpretation allows quantification of the more or less marked elongation (second harmonic), triangularity (third harmonic), quadrangularity (fourth harmonic), pentagonality (fifth harmonic), hexagonality (sixth harmonic) of the studied shapes. Thus, amplitude and phase values of the Fourier harmonics are highly informative for a better understanding of the shape differences between the handwritten characters studied. This approach presents a new way to describe handwritten characters and allows for the quantitative study of their global morphological aspects.

A polymorphism can be characterized quantitatively and objectively by statistical analysis of the amplitudes and phases of Fourier harmonics. Within-writer variability of the shape of capital characters O for the writers selected could be shown, as indicated by the extent of the clouds of points representing individual characters on the graph resulting from the discriminant analysis (Fig. 6). The polymorphism was expressed by the variance of the data in each group, this variance being characterized by a mean distance between all pairs of points of a considered group. By comparing these distances, it was possible to compare this polymorphism between the three writers studied. This polymorphism was more important in the third writer (W3) than in the first and the second writers (W1–W2).

Differentiation could be demonstrated between the three writers through this analysis, even if polymorphism was also observed within each of the groups of handwritten capital characters O. That was supported by the high morphological distances (i.e. Mahalanobis distances) between the three writers (Table 4). The calculated distances between the three groups of shapes made it possible to appreciate the degree of dissimilitude of the capital character O writings. For instance, according to the obtained distances, the capital O writing of the first writer was more dissimilar to the capital O writing of the third one than to the capital O writing of the second one.

A morphological profile was demonstrated by morphological quantification and by the existence of relatively reduced within-writer variability and a marked differentiation between the writers; no overlapping between the three groups was observed when performing the discriminant analysis. The profiles were illustrated by polar representations (Fig. 3). The morphological differences were highlighted by the differences in position between the clouds of points for each writer and Fourier harmonics. The morphological profiles supported the two fundamental requirements for discrimination between writers: the existence of constant aspects in any one handwriting, as well as differences between handwritings.

Discrimination between several writers could be obtained through the quantification of the shape of one handwritten character. This is an interesting perspective for the examination of fragmentary documents, containing a reduced amount of handwriting information. Finally, if useful information can be obtained through letter O, it could be assumed that it will be the same for other handwritten characters. Consequently, it would be interesting to extend the present validation study to other handwritten characters, in order to further contribute to testing the fundamental laws of handwriting.

Acknowledgements

This work was supported by a research grant (1114-066787.01/1) from the Swiss National Science Foundation. We thank the referees for their fruitful comments on the first version of this paper.

References

[1] D.M. Risinger, M.P. Denbeaux, M.J. Saks, Exorcism of ignorance as a proxy for rational knowledge: the lessons of handwriting identification expertise, U. Pa. L. Rev. 137 (1989) 731–792.

[2] O. Galbraith, C.S. Galbraith, N.G. Galbraith, The principle of the Drunkard's search as a proxy for scientific analysis: the misuse of handwriting test data in a law journal article, Int. J. Forensic Doc. Examiners 1 (1995) 7–17.

[3] A.A. Moenssens, Handwriting identification evidence in the post-Daubert world, U. M. K. C. L. Rev. 66 (1997) 251–310.

[4] D.M. Risinger, M.P. Denbeaux, M.J. Saks, Brave new ″post-Daubert world″—a reply to Professor Moenssens, Seton Hall L. Rev. 29 (1998) 405–485.

[5] A.A. Moenssens, Meeting the Daubert challenge to handwriting evidence: preparing for a daubert hearing, Forensic Sci. Com. 1 (1999).

[6] United States v. Starzecpyzel, 880 F. Supp 1027 (S.D.N.Y. 1995).
[7] Daubert v. Merrell Dow Pharmaceuticals Inc., U.S. 113 S. Ct. 2786 (1993).
[8] R.N. Morris, Forensic Handwriting Identification, Academic Press, London, 2000.
[9] E.H.W. Schroeder, A revised method of classifying fraudulent checks in a document examination laboratory, J. Forensic Sci. 19 (1974) 618–635.
[10] L.R. Taylor, H. Chandler, A system for handwriting classification, J. Forensic Sci. 32 (1987) 1775–1781.
[11] R.A. Hardcastle, D. Kemmenoe, A computer-based system for the classification of handwriting on cheques. Part 2: cursive handwriting., J. Forensic Sci. Soc. 30 (1990) 97–103.
[12] O.B. Livingston, Frequency of certain characteristics in handwriting pen-printing of two hundred people, J. Forensic Sci. 8 (1963) 250–259.
[13] R.J. Muehlberger, K.W. Newman, J. Regent, J.G. Wichmann, A statistical examination of selected handwriting characteristics, J. Forensic Sci. 22 (1977) 206–215.
[14] J. Zimmerman, Frequency of omission, perseveration and reversals in handwriting and relative value as individual characteristics, J. Forensic Ident. 40 (1990) 127–134.
[15] R.A. Horton, A study of the occurrence of certain handwriting characteristics in a random population, Int. J. Forensic Doc. Examiners 2 (1996) 95–102.
[16] J. Zimmerman, Counting handwriting characteristics, Int. J. Forensic Doc. Examiners 4 (1998) 318–322.
[17] A. Crane, The frequency of round handwriting in Edmonton Alberta Schools, Can. Soc. Forensic Sci. 32 (1999) 169–174.
[18] A.M. Wing, I. Nimmo-Smith, The variability of cursive handwriting measure defined along a continuum: letter specificity, J. Forensic Sci. Soc. 37 (1987) 297–306.
[19] S.N. Srihari, S.-H. Cha, H. Arora, S. Lee, Individuality of handwriting, J. Forensic Sci. 47 (2002) 857–872.
[20] W. Kuckuck, Computer-aided Identification of Handwriting. In: Police Research in the Federal Republic of Germany (Kube E., Störzer H.), Springer-Verlag, Berlin, 1991.
[21] C. Greening, V.K. Sagar, G. Leedham, Forensic document examination with automatic separation of handwritten and machine-printed text. In: Handwriting and Drawing Research: Basic and Applied Issues (Simner M., Thomassen A.), IOS Press, Amsterdam, 1996.
[22] A. Buquet, La Vérification Automatisée des Ecritures et des Signatures, RIPC 483 (2000) 10–18.
[23] H.E.S. Said, T.N. Tan, K.D. Baker, Personal identification based on handwriting, Pattern Recognition 33 (2000) 149–160.
[24] W.R. Harrison, Suspect Documents; Their Scientific Examination. Second Impression, Sweet & Maxwell Limited, London, 1966.
[25] R.C. Hanlen, P.A. Manzollilo, R.J. Muehlberger, G.R. Sperry, Survey of handwriting habit areas used by forensic document examiners: degree of use and discriminatory power, J. Am. Soc. Quest. Doc. Exam. 2 (1999) 45–50.
[26] P. Palmqvist, J.A. Pérez-Claros, J. Gibert, J.L. Santamaría, Comparative morphometric study of a human phalanx from the lower pleistocene site at Cueva Victoria (Murcia, Spain), by means of Fourier analysis, shape coordinates of landmarks, principal and relative warps, J. Arch. Sc. 23 (1996) 95–107.
[27] M. Schmittbuhl, J.-M. Le Minor, B. Allenbach, A. Schaaf, Shape of the piriform aperture in Gorilla gorilla, *Pan troglodytes*, and modern *Homo sapiens*: characterization and polymorphism analysis, Am. J. Phys. Anthropol. 106 (1998) 297–310.
[28] P.E. Lestrel, Fourier descriptors and their applications in biology, Cambridge University Press, Cambridge, 1997.
[29] B. Everitt, S. Rabe-Hesketh, Analyzing Medical Data Using S-Plus, Springer-Verlag, New York, 2001.
[30] D. Cheng, R.K. Ward, H. Yan, Recognition of handwritten numerals using topological structures and fourier descriptors of numeral contours, Can. J. Electr. Comput. Eng. 24 (1999) 73–83.
[31] D. Zhang, G. Lu, Shape-based image retrieval using generic fourier descriptor, Signal Processing: Image Commun. 17 (2002) 825–848.