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## A new method for measuring pen pressure in forensic handwriting analysis – a proof of concept study

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This work describes a new method for the analysis of handwritten documents through a system composed of a pre-selector optical analyser equipped with light sources of different wavelengths coupled with bandpass filters combined with an optical coherence tomography (OCT) instrument. The optical analyser identifies regions with different pen pressures on the paper using specific wavelengths from ultraviolet (UV) to infrared (IR) and bandpass filters. Then the selected regions are analysed with a coherence tomography analyser to measure the depth of grooves and capture three-dimensional images. With this methodology, it is possible to identify similarities, or differences, between the pieces of evidence under investigation, increasing the possibility of correct attribution concerning the authorship of the signature and we also showed that this feature is independent of the paper substrate. In this work, a new strategy will be presented to categorize and quantify pen pressure in order to aid a better response for a forensic examiner. Thereby, from the observed areas that display higher pressures (more significant grooves), it is possible to determine the authorship of the signature.

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### 1. Introduction

The forensic investigation of manuscripts has the main objective of verifying authenticity and authorship and is based on two fundamental principles and four laws of writing, which support the investigation of alleged forgery.<sup>1</sup> The first fundamental principle states that writing is an individual characteristic, being created from brain stimuli, and the second reports that regardless of the alphabet used, the laws of writing remain the same.

The first law of writing states that, since writing emanates from the brain, it cannot be consciously modified by the writer; the second refers to the unconscious feeling in writing, being the effort to perform writing, related to the conscious and the subconscious; the third explains that it is very difficult to voluntarily change the usual way of writing without leaving marks of this attempt to change; and the fourth says that when circumstances require an effort to alter one's own writing, the individual leaves evidence of that effort in his/her action.<sup>1,2</sup>

One of the most striking features of an individual's writing is the differential pen pressure, which corresponds to the variable axial pen force (APF) that the instrument exerts on the

paper in handwriting. Different methods have been proposed for the measurement of APF. Shomaker and Plamondon proposed that measurements should be done directly, through sensors or transducers coupled directly to the writer's fist, in order to measure not only the APF but also its temporal dependence, which gives information on the development (or speed) of writing and introduces a longitudinal vector component.<sup>3</sup>

The importance of hand pressure as an element that can be used to identify the writer and determine some of his/her psychological characteristics has long been highlighted by experts in forensic document analysis, and the importance of APF as a critical element in the individualization of writing is recognized by the fact that it is practically impossible to reproduce it in a forgery.<sup>4,5</sup> Despite this, the specialized literature covers a very small number of studies in this regard.

In another approach, Baier and co-workers proposed a methodology to APF determination measuring the width and depth of the trace by microscopy or by the characteristics of the paper.<sup>6</sup> In biological cybernetics, human arm movements have been analysed with advanced mathematical, microscopic and physical models. An intensive study in the neuroscience of handwriting from a forensic point of view is presented in a book by Caligiuri and Mohammed.<sup>7</sup> Nevertheless, such research, while involving scientific processes, is still nowadays of little practicality for forensic document analysts.

Forgery and adulteration of documents, such as identity documents, titles, passports, certificates, driver's licenses, and

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others, are increasingly frequent so fast, non-destructive, efficient and reliable methods are needed to obtain results quickly and with high reliability, especially in cases involving police investigation, where rapidity and confidence are required.

It is necessary to consider that to carry out the analysis it is strictly forbidden to damage the documents in hand, even after the samples are collected because some of its parts could be compromised, even if not perceptibly to the naked eye. Only with the express authorization of the authorities could small samples be taken for physical or chemical analysis if these are the only methods available. Some forms of procedure, techniques or partially destructive tools, such as gas chromatography-mass spectrometry and scanning electron microscopy of fragments of the document (used when the material concerned is too large for the equipment) should be avoided whenever possible. With a judicial release, it is possible to use a destructive technique if it preserves the evidence/sample, which could be needed for future analysis or rebuttal, in a way that maintains the integrity of the documents.

In this work we present a new way of qualifying and quantifying pen pressure through two complementary techniques: optical inspection, through special illumination and use of narrow band filters, and measurement of pressure variation along the tracing through optical coherence tomography (OCT), which are both non-destructive techniques. To the best of our knowledge, this is the first direct measurement of APF.

In forensic sciences, the use of OCT has attracted the interest of researchers, notably in the field of medicine, with different objectives. Napoli *et al.* studied the applicability of the technique in measurements of the corneal thickness of sheep at different post-mortem periods, showing that the method has adequate reproducibility and repeatability to make the method feasible.<sup>12</sup> A review of the applications of OCT in forensic medicine offers an insight into the current development of the technique and its use in autopsies and virtual histologies, which is identified as a future challenge in legal medical fields<sup>13</sup> and also in the forensic study of document verification, as reported by Nioi *et al.*<sup>14</sup> In the area of human identification through fingerprints, preliminary studies show that OCT can also be useful for providing 3D images in biometric identification.<sup>15</sup>

Recent applications of the OCT method have expanded to medical biology, clinical pathology, cell biology, the material industry and even biometric-based forensic science.<sup>16–18</sup>

In what follows, we will focus our attention only on the axial force exerted by the instrument on the support in the case of a static image of the original signature (the result after the production of the signature). In other words, the actual conditions in which the writing was produced are unknown, as is common in forensic handwriting analysis.

We start from the result in search of the tracing characteristics since the observation of the differential pressure provides a very important technical element for the recognition of forgery. On the other hand, we take into account that, in the forensic field, the expert usually has few standards for com-



Fig. 1 The axial pen force (APF) related to the position of the pen. The normal force is related to the axial force by  $F_N = -F_A \sin \alpha$ .

parative analysis, and the present method provides a solid way to base a conclusion on the falsity or authenticity of a piece of writing, since pen pressure is an individualized element of writing, and some experts in the field call it a *genetic element* of the writer.

It is worthwhile to note that the axial force is different from the normal force. The APF responsible for the pressure that we consider is illustrated in Fig. 1 below. The normal force is related to the axial force by  $F_N = -F_A \sin(\alpha)$ .

This work presents a new methodology of handwriting analysis based on the sequential use of two optical techniques: multispectral optical filters (MOFs). In order to standardize the data readings, a mathematical algorithm was developed. An important element in this analysis is the differential pressure exerted by the writing instrument on different supports (paper sheets). Differential pressure is defined as the variations of the APF, which represent the force applied by the writer's wrist exerted over the stroke of text. It just depended on superficial observation and is very difficult to observe and even harder to quantify.

## 2. Materials and methods

### 2.1. Materials

All subjects enrolled in the study were volunteers who were informed in writing about its aim and provided written consent concerning the scientific use of the obtained data. The signatures of five healthy volunteers aged between 30 and 60 years were chosen, three were men and two were women. The signature of one of them was used as a standard. The signatures were affixed to sheets of four white A4 paper types (each volunteer used one sheet): sulphite paper 90 g m<sup>-2</sup>, ColorPlus 80, verge 90 and verge 120, using the same blue ball-point pen. When executing the signature, a block of five sheets was placed under the sulphite paper to be signed forming a soft base. Part of a personal name was used as the object of the analysis, see Fig. 5 and 6.

All participants were asked to sign 4 types of papers 10 times in triplicate, resulting in 120 signatures per volunteer or 150 signatures for each piece of paper. Initially, the main grooves in each document were identified using the optical analysis described below. Thereafter, the identified region of interest (ROI) was analysed by OCT. For each ROI 10 OCT images were obtained, totalling 1500 images per ROI analysed. In order to analyse the groove depths, and to avoid human misinterpretation, a computer algorithm was specially devel-

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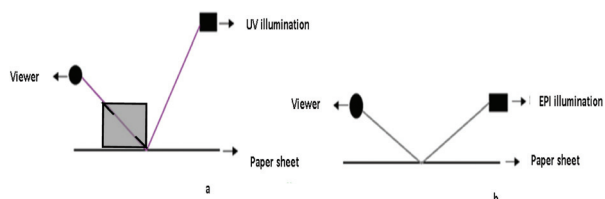
oped in a Labview® environment, allowing groove analysis in a fast and precise procedure.

In order to avoid the samples being damaged, they were stored in transparent plastic envelopes. In addition, care was taken so that no heavy object was placed on the envelopes containing the samples, in order not to alter the depth of the pen grooves caused by the wrist pressure exerted by each volunteer so as not to harm further analyses.

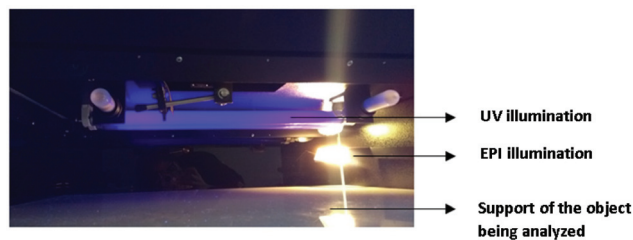
## 2.2. Optical analysis

As a previous selection to a more precise physical analysis, forty samples of forgery by imitation were collected based on the standard signature, ten for each substrate paper. This procedure saves much of the microscopic analysis time in the OCT. The five distinct volunteers were submitted to the same conditions (sitting and writing support) when trying to reproduce the original signature. The samples were taken for analysis inside the optical instrument, one at a time, and submitted to radiation by a sequence of different sources of wavelength from the UV (400 nm) to the IR (800 nm) regions, provided by the optical instrument Docucenter 2000 – Projectina® coupled to a notebook with VirtualDub software 2.0, with the purpose of identifying the areas of greatest pressures of the signatures performed by each volunteer, based on the observation of the depth of the grooves left by the pen. At each step, filters were interposed between the reflected radiation and the detector. The optical instrument offers sources of light of different wavelengths, such as IR light, UV light, and EPI lighting (a side white lamp that helps to enhance the relief of the analysed document) and has monochromatic passband filters, which serve as a barrier to certain types of radiation (Fig. 2 and 3). The best result was obtained using a UV light and a passband filter of 780 nm after the introduction of barrier filters in the infrared region. With this incident light, absorption of the ink from the pen occurs, in order to aid better observation of the areas of interest. EPI lighting, along with UV light, enhances the sharpness of the analysed image. The wavelength filter of 780 nm provides better observation of the areas of more marked grooves, that is, areas where greater pressures were exerted when signing.

From the analysis, by inserting the passband 780 nm filter incident to ultraviolet light (UV) and flat surface light (EPI – side light) – which was shown to be most suitable – it was possible to observe the areas with higher pressures due to the



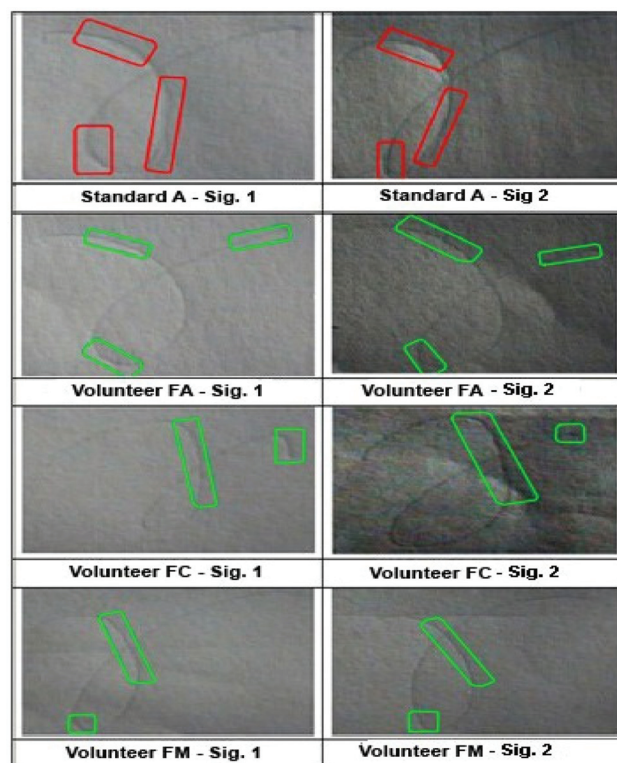
**Fig. 2** A scheme of the optical instrument operation: (a) UV illumination reflecting on the paper sheet surface with a bandpass filter interposed; (b) EPI illumination reflecting on the paper sheet surface.



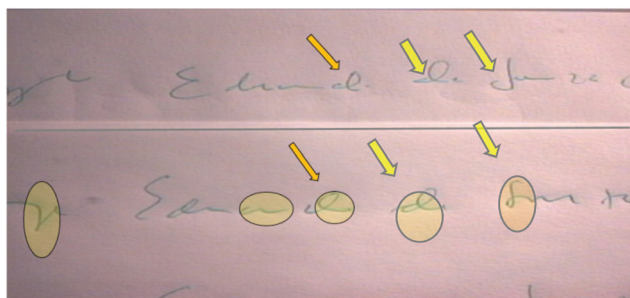
**Fig. 3** An image of the UV and EPI lighting operating at Docucenter 2000 (Projectina®).

writer's instrument grooves (grooves made by pen pressure over the papers sheets), allowing observation and comparison of the areas with higher pressured signatures from the four volunteers that were trying to forge the standard one (Fig. 4).

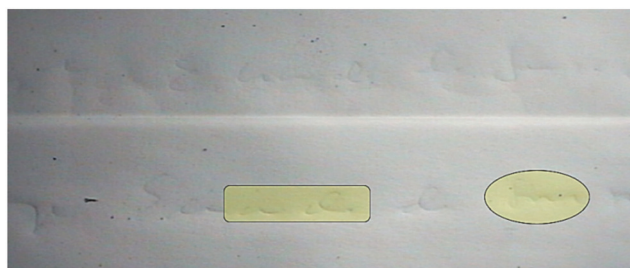
As is possible to observe in Fig. 4, the standard (first line) and three volunteers' signatures exhibit different areas with higher pressures. Besides that, each one showed their own unique pressured areas, which means that the high-pressure area of an individual was always different from each other. Although this technique can show different areas of pressure, it cannot measure the grooves with adequate precision for forensic analysis. To perform these measurements, the regions shown in Fig. 5 and 6 were chosen for analysis by OCT.



**Fig. 4** Two standards (first line) and three repeated forgeries of the initial trace of the signature using the UV light wavelength and 780 nm filter (right) and with the EPI light (left): the red and the green rectangles on the forged signatures on the right show the areas of different pressure between them (more significant grooves).



**Fig. 5** Above: Enlargement of two regions of interest. Below: The standard signature in full (first line above) compared to the false signature (below), showing regions of different wrist pressures between them, with UV illumination and a filter of 780 nm. The letters indicated by arrows were selected to illustrate the analysis.

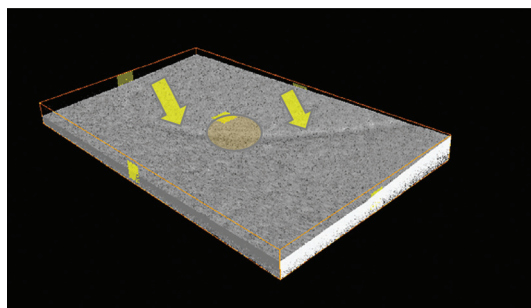


**Fig. 6** The same image with highlighted regions of different pressures with white illumination and a filter of 780 nm.

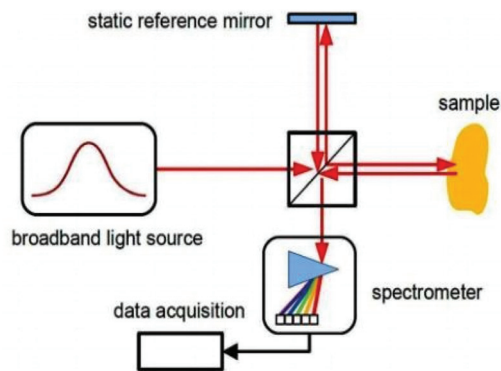
### 2.3. OCT technique

After the selection of the samples by an optical process, they were analyzed by OCT to achieve a precise measurement of the substrate paper grooves, as we can see in a 3D reconstructed paper surface as shown in Fig. 7.

Optical coherence tomography (OCT) is a technique that uses IR light to produce tomographic images from scattering media. It can provide sectional images of structures, in high-resolution, non-invasively, using non-ionizing radiation and in real-time.<sup>8,9</sup> Information about the material like the optical scattering coefficient, birefringent property and others are col-



**Fig. 7** An example of a 3D OCT image of a ballpen groove. The pen pressure is constant along the entire groove (frame velocity  $8.5 \text{ Fr s}^{-1}$ , length scanning 2 mm).



**Fig. 8** A Fourier domain OCT diagram. The scattered light from the sample and the reflected light from the reference mirror are combined to generate a spectral interference on the spectrometer.

lected as a function of the sample depth (A-Scan) and are used to construct a cross-sectional image (B-Scan) in real time as shown in Fig. 7. Analogous to ultrasound, OCT measures the backscattering intensity of an infrared laser rather than sound. Once the backscattering intensity as a function of depth cannot be measured directly due to the high speed of the light, the OCT uses a technique known as low coherence interferometry. Despite generating cross-sectional images (2-D) of the tissues as in microscopy, in OCT the samples do not need any prior preparation, which prevents any changes in tissue.<sup>10</sup> Moreover, thin cross-section images may be used to recreate the three-dimensional structure of the samples.<sup>11</sup>

A schematic diagram of OCT operation is shown in Fig. 8.

By using the OCT system, one achieves ultrahigh spatial resolution down to 6.0 micron with high sensitivity and obtains scan-free OCT imaging at a speed of 8.5 frame per s. The depth-resolved imaging capability of the scheme enabled tomographic identification of superficially identical objects.

In this work the images were obtained with OCP930SR (Thorlabs Inc., USA) with a spatial resolution of 6.0 microns, using a superluminescent SLED@930 nm with 2 mW of power.

The ten samples cited above were analysed by OCT covering a region of  $8 \times 2$  millimetre of the paper sheet and the 3D images were generated from OCT raw data, using VGStudioMax 2.2 (VolumeGraphics GmbH).

## 3. Results

Tomographic image regions pre-selected by MOF, as shown in Fig. 5 and 6, were analysed by the OCT technique.

The samples were divided into two groups, the first one was denoted “authentic” and labelled with the letter “A”, and the second, the “false” group was labelled with an “F”. Two letters, lower case “d” and upper case “S”, were chosen for a demonstration of the method (see Fig. 5) so the label “NDA(NDF)” or “NSA(NSF)” means “image number N” of the letter “d” (“S”) from the “authentic” (“false”) sample, for example “1SA” means image “1”, letter “S” authentic, and so on. The pen

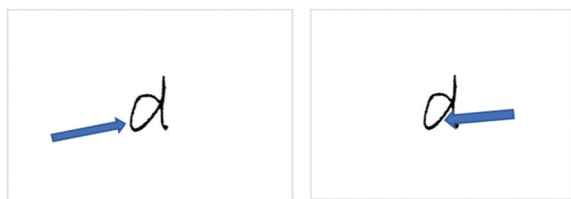


Fig. 9 The location of measurements made to the left and right of the selected letter from top to down.

pressure was measured on both sides of each one (right and left) and the measurements were made from the top to the base in each sample (see Fig. 9). Correlated regions of each pair of samples were analyzed in the OCT and the depth of the paper grooves was measured. Two selected tomographic images are shown in Fig. 10 and 11 for comparison of the authentic and false groups both sides of letter “S”. All the results are plotted in Charts 1–6 where the measurements are in micrometres.

Measurements of the depths caused by the pen pressure show that the “false” samples always have a lower depth, which can be understood as indicating the impossibility of a forger to add the factor “pen pressure” in his intention.

Charts 1–6 show the values of the measurements of the differential depth grooves of each selected sample in micrometres. These data are exposed in pairs of corresponding tables “authentic – false”. Comparing the results showed in Charts 1 and 2, for example, one can observe the great difference in depth between the two samples. In the “authentic” group, the measured depths are, in general, much greater than the correlated measurement of the “false” sample. One can also observe that the end of the analysed trace in the “authentic” sample at the left side has null depth, indicating an evanescent end and showing a characteristic of the writer. At the right side, however, the beginning of the trace is evanescent.

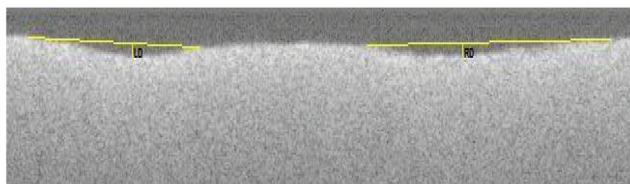


Fig. 10 Sample 1SA (letter “S”, authentic) – depths at the left and right sides.

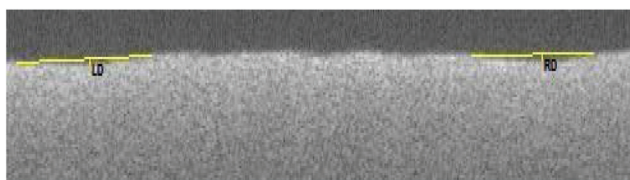


Fig. 11 Sample 1SF (letter “S”, false) – depths at the left and right sides.

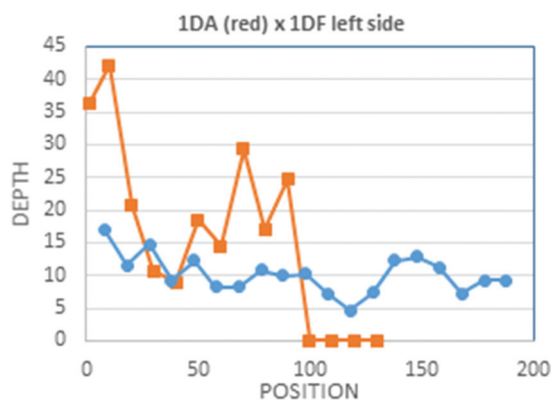


Chart 1 Comparative depth measurement in the left side of the first letter “D” – authentic sample (red) × false sample (blue).

Another important feature of “authentic” writing can be seen by analysing the measurements on the left side of the first letter “d” (sample “1DA”). It can be observed that in Chart 1 the “authentic” writing (red line) starts with a higher pressure and ends with zero pressure (vanishing stroke). As the measurement was made in descending order of the letter, it can be inferred that the stroke of the first letter “d” was done in an anti-clockwise direction, starting from the left side. On the other hand, in Chart 2, corresponding to the right side, the opposite occurs: the beginning has zero pressure and the final has higher pen pressure. Possibly the difference between the two “d’s” is because the former is in the middle of two other letters, while the second is at the beginning of the stroke.

The average depth in the authentic sample is 50% greater than the same region of the false sample. This is a feature that is reproduced in all the other samples and a proof that, even in a “good” forgery, the pen pressure cannot be reproduced by the forger.

Many other features can be seen in the Charts 1–6 inspection below. False signatures, in general, have a nearly constant pressure trend line, with some exceptions, which is perfectly expected in the case of falsity per copy.

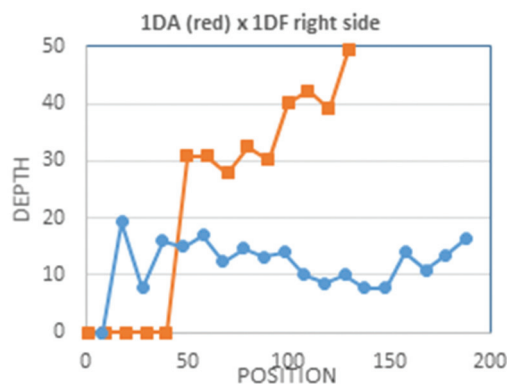


Chart 2 Comparative depth measurement in the right side of the first letter “D” – authentic sample (red) × false sample (blue).



Chart 3 Comparative depth measurement in the left side of the second letter "D" – authentic sample (red) x false sample (blue).

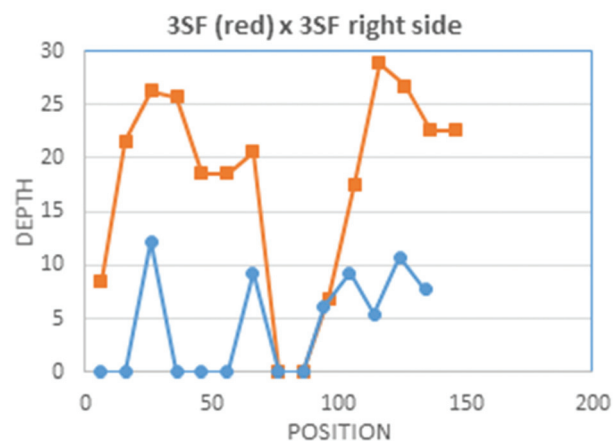


Chart 6 Comparative depth measurement in the right side of the letter "S" – authentic sample (red) x false sample (blue).

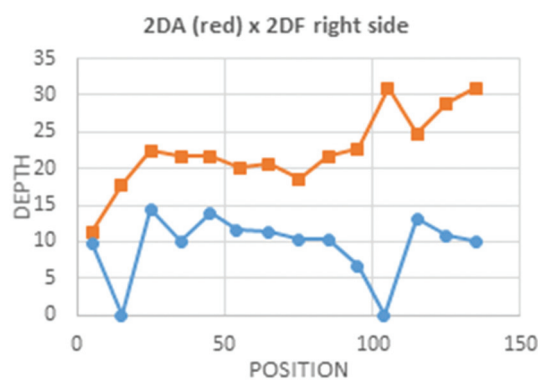


Chart 4 Comparative depth measurement in the right side of the second letter "D" – authentic sample (red) x false sample (blue).

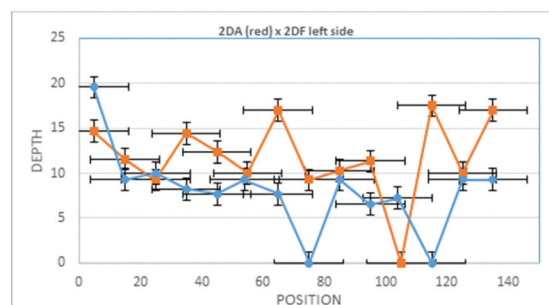


Fig. 12 Standard error in measurement in Chart 3.

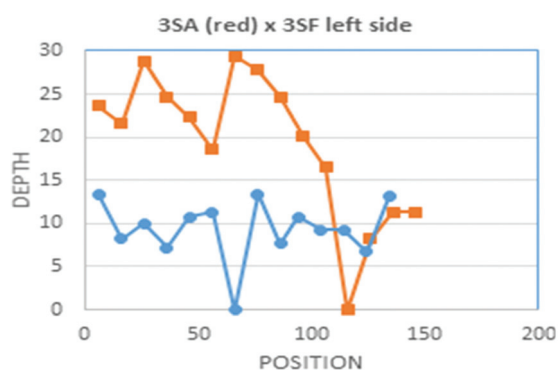


Chart 5 Comparative depth measurement in the left side of the letter "S" – authentic sample (red) x false sample (blue).

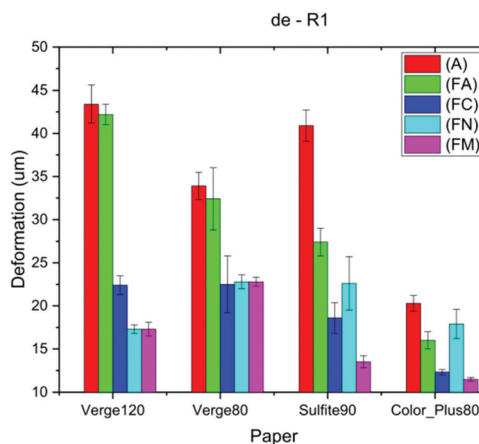


Fig. 13 Groove of paper as a function of paper type. Different types of paper showed that the pen pressure exerted by the volunteers changes with the type of paper, however, the difference between all the volunteers remains. This figure is an example of a ROI labelled as letter "d", group "de" of the signature.

Fig. 12 shows the standard errors in the case of the measurements of the depth on the left side of the second selected letter "d" in Chart 3, where the pressures of the authentic and false samples are closer and one can see that the measurements are reliable even in this case.

The study on different types of paper showed that the pen pressure exerted by the volunteers changes with the type of

paper, however, the difference between all volunteers remains. This shows that the analysis result is independent of the paper substrate. In Fig. 13 and 14, we can observe this behaviour.

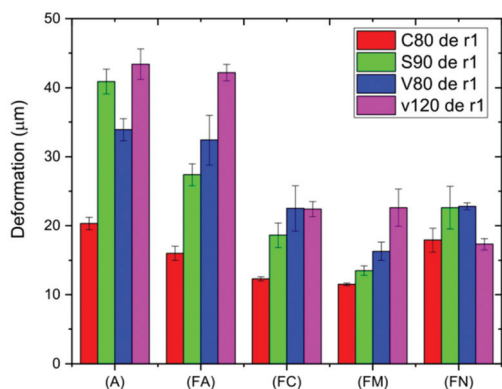


Fig. 14 Groove of paper as a function of each volunteer. It can be seen that different types of papers presented a similar behaviour. The ROI is the same as Fig. 13.

Fig. 13 shows that each volunteer applies a different pressure for each kind of paper. In Fig. 14 it can be seen that different types of paper presented a similar behaviour, we can observe that the groove due to pen pressure depends on the paper type, and in most cases follows the same pattern, except (FN). The smallest grooves were observed for C80 (colour 80 paper), and the biggest were observed for verge paper for all the volunteers.

Table 1 Summary of the statistical analysis for letter "d"

Volunteers	Statistical difference (5% significance level)			
	Verge 120	Verge 80	Sufite 90	Color plus 80
A	FN, FM	FC, FM, FA	FM, FC	FM, FC, FA
FA	FN, FM	A	FM, FC	FN, A
FC		A	FM, FN, FA, A	FN, A
FM	FA, A	A	FC, FN, FA, A	FN, A
FN	FA, A			FM, FC, FA

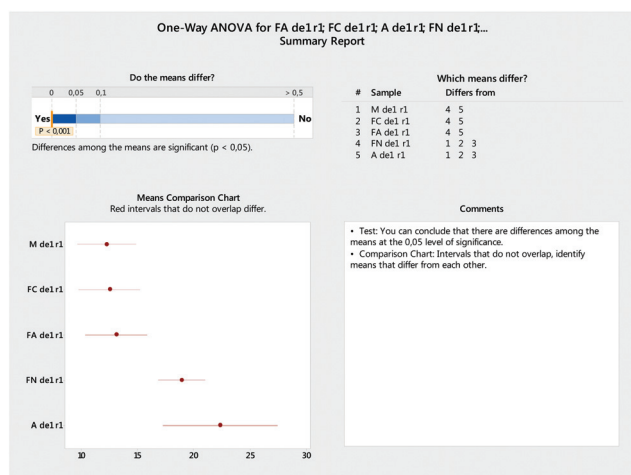


Fig. 15 One-way ANOVA summary report for letter "d".

## 4. Statistical analysis

Statistical analysis was performed using Minitab® 18.1 with the Welch method which can be used with data with different variances. One-way ANOVA was used to compare more than two samples within the significance level of 5%. The letter "d" in each signature was used as the reference and the base of the statistical analysis. Table 1: all the "d" letters present in the volunteers' signatures were compared with the one considered as authentic.

Fig. 15 shows the summary report for letter "d", the same analysis is carried out for all regions.

## 5. Conclusions

The strategy to use MOF to pre-define the regions to be analysed by OCT was demonstrated to be effective since it improves the efficacy of the methodology with a significant time consumption. An important tool specially developed for this study was the mathematical algorithm for collection and data analysis. Its use made possible the obtention of reproducible and reliable data avoiding potential errors due to human interpretation and creating a way to standardize this type of analysis which does not have reference materials. The UV source used did not cause any damage to the samples when the documents were exposed to light for less than 2 minutes. EPI lighting did not result in any damage to the documents and ensured greater image clarity. On the other hand, OCT, as well as being a non-destructive technique, provides precise measurement of the depth of the trace of the pen, and thus renders analytical a hitherto somewhat subjective analysis. Therefore, it is expected that the developed methodology has potential as a new non-invasive tool to discern imitations of currency and furthermore, in applications identifying signatures, handwriting, certificates, credit cards and various other security documents.

As shown in the measurements performed, the difference in pen pressure between the authentic and false writing is evident, with the pressure of authentic writing always being greater than the false. Even in the case of the second lower-case letter "d", where the pressures become equivalent, this happens even if one considers the standard errors shown in Fig. 12. Comparative measurements made on the right side between the pressures of the second authentic and false letter "d" including the standard error, show the reliability of the measurements.

We found also that even when changing the substrate paper, the groove pattern between all the volunteers remains the same (Fig. 13 and 14). This finding shows that the technique has good precision and usefulness for forensic purposes.

As shown in this paper, according to the data obtained, it is possible to observe the different areas where the wrist pressures were more significant, and, more importantly, these areas are very different among the "authentic" and the "false" signatures. This fact can by itself prove the forgery of a signature, provided that the original written pen paths are made available, and the present method provides a solid way to base a

conclusion on the falsity or authenticity of a writing. So, authenticity or forgery can be concluded as a result of the different areas of pressure of the standard and the volunteer's signatures due to the individuality during the act of writing.

## Data availability

The data that support the findings of this study can be accessed from the corresponding author upon reasonable request.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

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