JOURNAL OF FORENSIC SCIENCES

J Forensic Sci, January 2018, Vol. 63, No. 1
doi: 10.1111/1556-4029.13491
Available online at: onlinelibrary.wiley.com

TECHNICAL NOTE

QUESTIONED DOCUMENTS

Chi-Keung Li,[1] Ph.D.; Siu-Kay Wong,[1] Ph.D.; and Lai-Chu Joyce Chim,[1] Ph.D.

A Prototype of Mathematical Treatment of Pen Pressure Data for Signature Verification*

ABSTRACT: A prototype using simple mathematical treatment of the pen pressure data recorded by a digital pen movement recording device was derived. In this study, a total of 48 sets of signature and initial specimens were collected. Pearson's correlation coefficient was used to compare the data of the pen pressure patterns. From the 820 pair comparisons of the 48 sets of genuine signatures, a high degree of matching was found in which 95.4% (782 pairs) and 80% (656 pairs) had rPA > 0.7 and rPA > 0.8, respectively. In the comparison of the 23 forged signatures with their corresponding control signatures, 20 of them (89.2% of pairs) had rPA values < 0.6, showing a lower degree of matching when compared with the results of the genuine signatures. The prototype could be used as a complementary technique to improve the objectivity of signature examination and also has a good potential to be developed as a tool for automated signature identification.

KEYWORDS: forensic science, documents examination, pen pressure pattern, signature identification, pearson's correlation coefficient, prototype

Pattern recognition has been widely used in forensic science, from analysis of unknown chemical compounds to person identification. The identity of a person can be determined or verified through pattern recognition of his biometric traits such as fingerprint, palm print, face, iris, retina, ear, voice, signature, gait, hand vein, odor, or the DNA information (1). The biometric traits range from individual physical characteristics (such as fingerprint) to behavioral attributes (such as signature). In the analysis of unknown chemical compounds using infrared spectroscopy and mass spectroscopy techniques, there are specific algorithms being used to provide an objective matching score for identification purposes, whereas in disciplines such as handwritten examination, facial recognition, and fingerprint and shoeprint identification the examiners perform the comparison and evaluation of characteristic patterns.

In handwriting and signature examination, document examiners compare the characteristic writing features of the questioned handwriting with the control specimens. These features, including but not limited to line quality, writing movements, pen pressure variation, and proportion and spatial arrangement of strokes, are compared (2–5). The significance of the evidence is evaluated which relies on the experience and knowledge of the examiners. Finally, an opinion relating to the authorship of the questioned handwriting/signature is offered based on the evaluation.

It has been mentioned in the literature that natural pen pressure variations are an integral part of an individual's signature. The variations are individual to such an extent that it is highly unlikely to have two authors with well-developed signatures of normal length with the same pressure patterns. Besides, the pressure patterns of a well-developed signature of normal length are extremely difficult to duplicate in the forged signature (2–8). Signature verification computer systems using pen pressure as an identifying characteristic were developed since 1970s (9). However, normal course of business signatures were mostly written on pieces of paper and pressure patterns of the signatures could not be easily recorded or converted from the paper to be examined.

Nowadays, owing to the shortage of storage space, most of the documents with signatures written on paper are digitized through an optical scanner or recorder. With the emergence of advance computer technologies and the promotion of paperless offices, customers in commercial activities such as banking, insurance, and courier and postal services are requested to sign on the writing pad and the image of the signatures are stored as digitized form. Some literature reported that the photocopied signatures could still be identified with a high degree of accuracy (3,10,11); however, when the quality of the disputed digitized signatures is comparatively inferior and lacking clarity for examination, it would be more difficult to determine the authorship of these signatures, as some crucial characteristic writing features such as pen pressure variation, sequence, and connection of strokes might not be able to be unambiguously determined from the reprinted signatures.

Research on various computerized methods for online signature verification has also been reported (12–17). Mohammed *et.al* (18) studied the effect of writer style on genuine and simulated signatures based on the computer-measured dynamic features (duration, velocity, jerk, and pen pressure). His study suggested that the normal writing style of the simulator had a significant effect on the writing dynamics for the simulated signatures. Recently, many digital pen movement recording devices have been launched in the market, and these pen movement

[1]Government Laboratory, Ho Man Tin Government Offices, 88 Chung Hau Street, Kowloon, Hong Kong Special Administrative Region, People's Republic of China.

*Presented in the ANZFSS 23rd International Symposium on the Forensic Sciences, September 18-23, 2016, in Auckland, New Zealand.

Received 24 Oct. 2016; and in revised form 6 Feb. 2017; accepted 8 Feb. 2017.

recording systems capture not only the coordinates of the pen movements for pattern recognition, but also the dynamic writing features such as duration, pen pressure, velocity, and acceleration of the pens upon execution. The application of these recording devices in daily usage could facilitate document examiners in examining digitized signatures.

One of the major criticisms in forensic handwriting examination is the subjective nature in evidence interpretations, lacking objective value to support the results of examination. In 2009, the NAS Report challenged the forensic sciences in several disciplines including forensic handwriting examination and stated that most of the forensic disciplines that rely on subjective assessments of matching characteristics need to strengthen the scientific basis and develop rigorous protocols to guide these subjective interpretations and pursue equally rigorous research and evaluation programs (19).

In this study, a prototype using simple mathematical treatment of the pen pressure patterns has been derived. Pearson's correlation coefficient is used to determine the degree of matching of the pen pressure patterns between signatures. The correlations of pressure pattern among (i) genuine signatures of the same author, (ii) between genuine and simulated forged signatures, and (iii) between genuine and forged signatures by tracing method will be studied and discussed. The prototype provides a quantitative value to show the degree of matching of two signatures could be used as a complementary technique that improves the objectivity of signature examination. The prototype also has a good potential to be developed as a tool for automated signature identification.

Methods

Data Collection

Genuine Signatures—Genuine signature and initial specimens were collected using Wacom Intuos 4,5 Pro Inking Pen (KP 1302) and a Wacom Intuos Pro medium digitalized tablet (PTH-651) connected to a computer installed with Windows 7 and a commercial software MOVALYZER® version 6. The dynamic features such as pen pressure, time of execution, pen movements, and the x–y-coordinates of the writing strokes of the signatures and initials were recorded by the software. Each subject was requested to provide a set of 3 signatures or initials each time. A second or third set of signatures of the same author with the same signature design as the previous one was collected from each individual subject from 1 week to 3 months after the first set of specimens was collected. A total of 48 sets of signature and initial specimens obtained from 35 males and 13 female Chinese aged from 30 to 60 were collected. All the writers were colleagues of Government Laboratory and were randomly selected.

Simulated Signatures—The printouts of the genuine signature and initial specimens obtained were provided to three document examiners (refer to as forgers). The three document examiners have 6–25 years of experience in document examination. They were asked to choose from these genuine signatures and initials, and time was provided to practice the simulation of the model signatures and initials on paper before they were ready to write the simulated signatures and initials. The forgers were asked to write the simulated signatures and initials two times using a digitized tablet connected to a computer installed with the commercial software. After the specimens were collected, the forgers were asked to choose one that they felt were the "closest" as the simulated signatures and initials for comparison with the genuine signatures and initials. A total of 38 simulated signatures and initials were obtained.

Traced Forgery—The printouts of the genuine signature and initial specimens obtained were provided to three document examiners (refer to as forgers). They were asked to choose from these genuine signatures and initials, and time was provided to practice the tracing act. The forgers were asked to place the printouts of the model signatures and initials on the tablet and forged the signatures and initials by tracing the writing lines of the model signatures and initials. A total of 21 signatures and initials forged by tracing were collected.

Data Treatment

According to the literature, Pearson's correlation coefficient has wide applications for pattern recognition in analytical chemistry, for example, comparative analysis of mass spectral similarity in gas chromatography–mass spectrometry (20). In statistics, Pearson's correlation coefficient, commonly represented by the letter *r*, is a measure of the strength and direction of the linear relationship between two variables. For one dataset $\{x_1,..,x_i,..,x_n\}$ containing *n* values and another dataset $\{y_1,..,y_i,..,y_n\}$ containing *n* values, the formula for *r* is:

$$r = \frac{\sum_{(i=1)}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{(i=1)}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{(i=1)}^{n}(y_i - \bar{y})^2}}$$

where $\bar{x}$ and $\bar{y}$ are the mean of respective dataset.

Values of the Pearson's correlation coefficient, *r*, can range from −1 to 1. An *r* of −1 indicates a perfect negative linear relationship between variables, an *r* of 0 indicates no linear relationship between variables, and an *r* of 1 indicates a perfect positive linear relationship between the two variables.

The tablet combined with the software employed in this study is capable of recording the *x–y*-coordinates, time and pen pressure at each point of the signature written on it. The data are then exported in a sequential manner to other devices, such as a personal computer, for data processing.

Essentially, the pen pressure pattern is composed of two elements, *viz.* time and pressure. A signature with the sequential data of pen pressure plotted against time is shown in Fig. 1. It could be observed that the pressure pattern obtained resembles a chromatogram with peaks occurred at different retention times. The "peaks" observed should reflect the pen pressure sensed by the tablet for the corresponding stroke(s) of the signature. For simplicity, the summation of pressure recorded for all the points within a peak was taken as the "peak area." The sum of pressure for each stroke(s) could be directly used as variable for the correlation analysis and overall a coefficient rPA would then be obtained for the two signatures under examination. In this study, Pearson's correlation coefficient rPA, respectively, for the pen pressure pattern is the statistical technique used for comparing pen pressure pattern data extracted from any two different signatures, including the comparison between genuine and forged signatures.

Results

Comparison of Genuine Signatures

Fifteen sets of initials and 33 sets of signatures were obtained with the device, comprising a total of 302 signature and initial

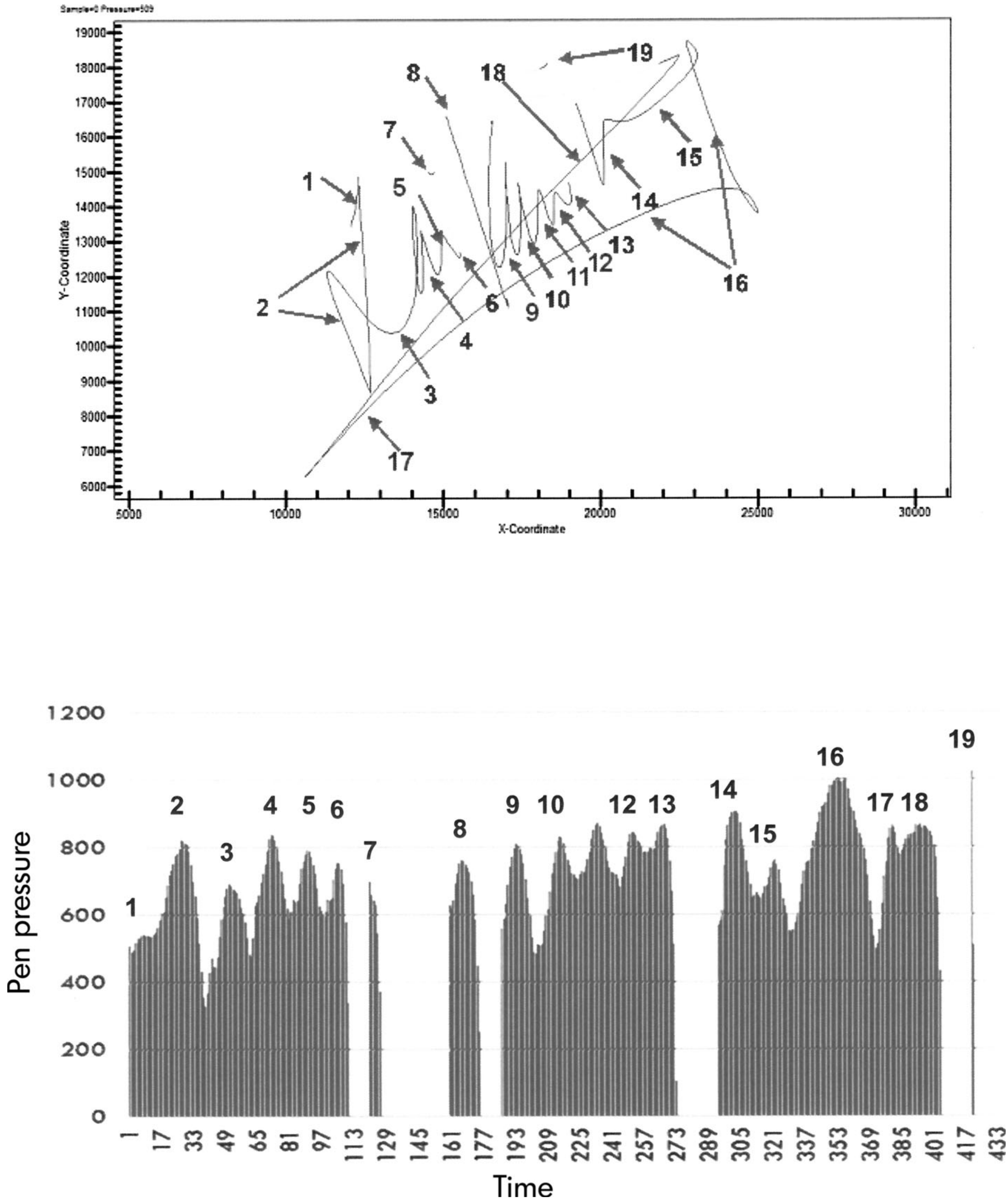

FIG. 1—*The graph of pen pressure versus time of a signature. The numerals illustrates the relationship between the peaks and the stroke segments.*

specimens. Each set of specimens was collected from the signatories at least two times to check if the specimens written at the same and different occasions matched each other. Among the 15 sets of initials, 3 signatories wrote 9 initials at three different occasions while 12 signatories wrote 6 initials at two different occasions. For the 33 sets of signatures, two signatories wrote 9

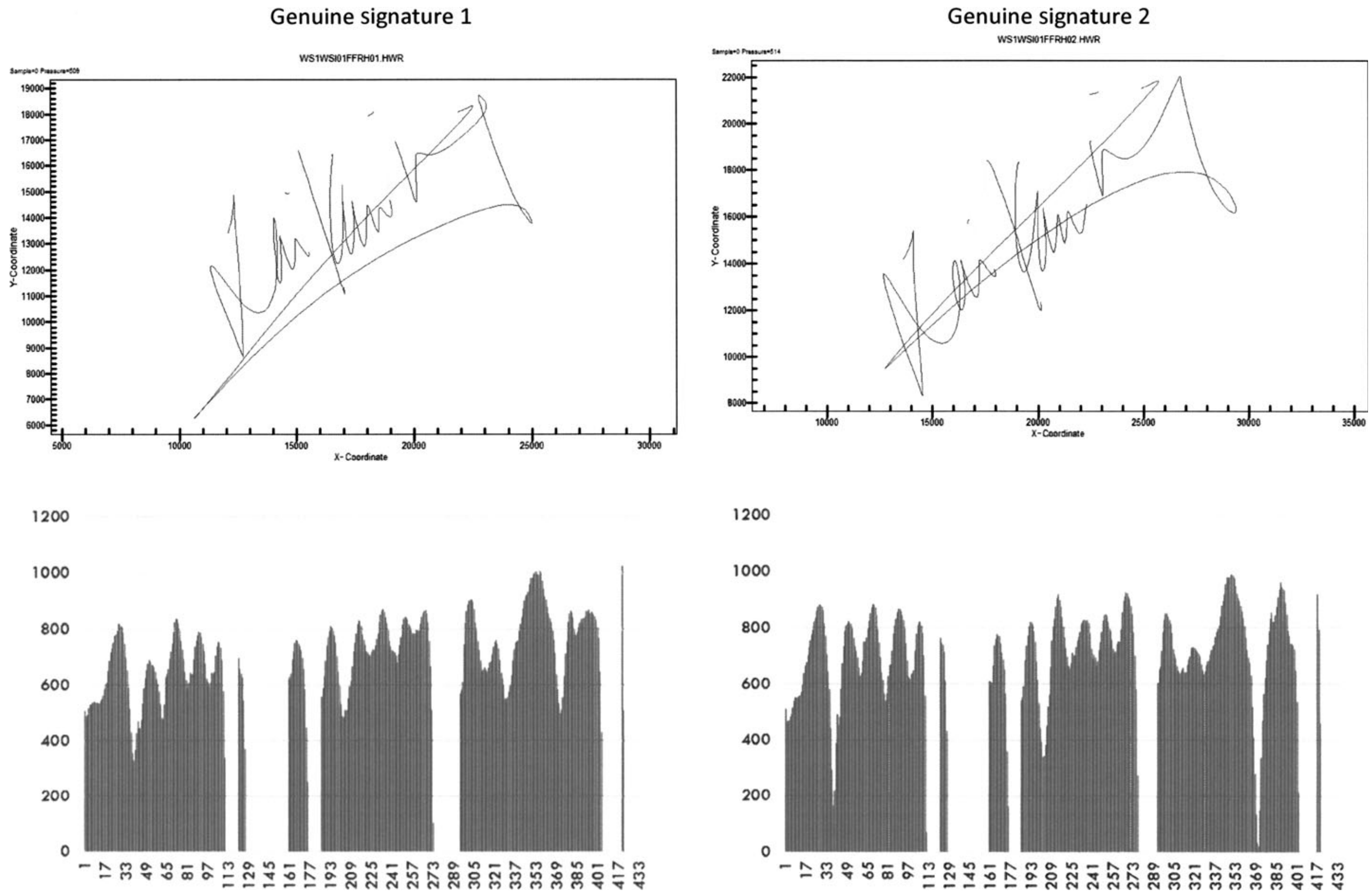

FIG. 2—*Graphs of pen pressure versus time of two genuine signatures from the same signatory.*

signatures at three different occasions, 30 signatories wrote 6 signatures at two different occasions, and 1 signatory wrote 5 signatures (tablet failed to collect data of one signature) on two different occasions.

As every signature has a unique design, it was found that the pen pressure patterns among the signatures from the same author resembled each other under visual comparison while the pen pressure patterns of the signatures from one writer could be easily distinguished from the others.

The segment of strokes could be related to the data of *x–y*-coordinates, which could be further related to the peaks on the pressure pattern graph as shown in Fig. 1. The pressure patterns of two genuine signatures 1 and 2 from the same signatory are illustrated in Fig. 2. The set of data containing the summation of pen pressure of each peak on the pressure pattern graph of genuine signature 1 was compared with the set of data from genuine signature 2 as given in Table 1, and the graphs showing the summation of pen pressure of each peak versus the peak number of the two genuine signatures 1 and 2 are illustrated in Fig. 3. The Pearson's correlation coefficient rPA related to summation of pen pressure of each peak of these two signatures was found to be 0.95.

Variation in Genuine Signatures

The arm, hand, and fingers constitute the motor part of the writing mechanism. However, they could not reproduce the handwriting with the precision of a machine, and therefore, all signatories display natural variation in their writing as shown in Fig. 4. External influences during the execution may also lead to occurrence of accidental features. As indicated by the red arrows in Fig. 4, extra stroke or structure was found in the genuine signatures G2 and G3 and extra peaks corresponding to these extra stroke or structure were also observed in the pressure pattern graphs.

TABLE 1—*Summation of pen pressure of each peak of the two genuine signatures 1 and 2.*

Peak No.	Σp_1 for Signature 1	Σp_2 for Signature 2
1	6288	5142
2	17685	19370
3	13025	13929
4	13548	15048
5	11829	14287
6	7828	8809
7	3537	4018
8	10413	10229
9	13177	11703
10	13615	14967
11	16224	15889
12	10384	10918
13	11135	14160
14	16606	15917
15	10110	10441
16	34574	32083
17	8976	7705
18	16082	15014
19	1532	2177

FIG. 3—*Graph of summation of pen pressure of each peak versus the peak number of the two genuine signatures 1 and 2. [Color figure can be viewed at wileyonlinelibrary.com]*

Pearson's correlation coefficient could still be used in dealing with natural variation in these genuine signatures. The comparison of these signatures could be conducted by ignoring the peaks of the extra stroke/structure (peak 10 and peak 4 in genuine signatures G2 and G3, respectively). The summation of pen pressure of each peak on the pressure pattern graphs of the three genuine signatures G1, G2, and G3 is listed in Table 2, and the graphs showing the summation of pen pressure of each peak versus the peak number of the three genuine signatures 1, 2, and 3 are illustrated in Fig. 5. Pearson's correlation coefficient rPA between G1 and G2, G2 and G3, and G3 and G1 were found to be 0.94, 0.94, and 0.88, respectively.

A total of 820 pair comparisons were made among the 48 sets of signature and initial specimens. The Pearson's correlation coefficient of each pair of comparison was calculated, and the

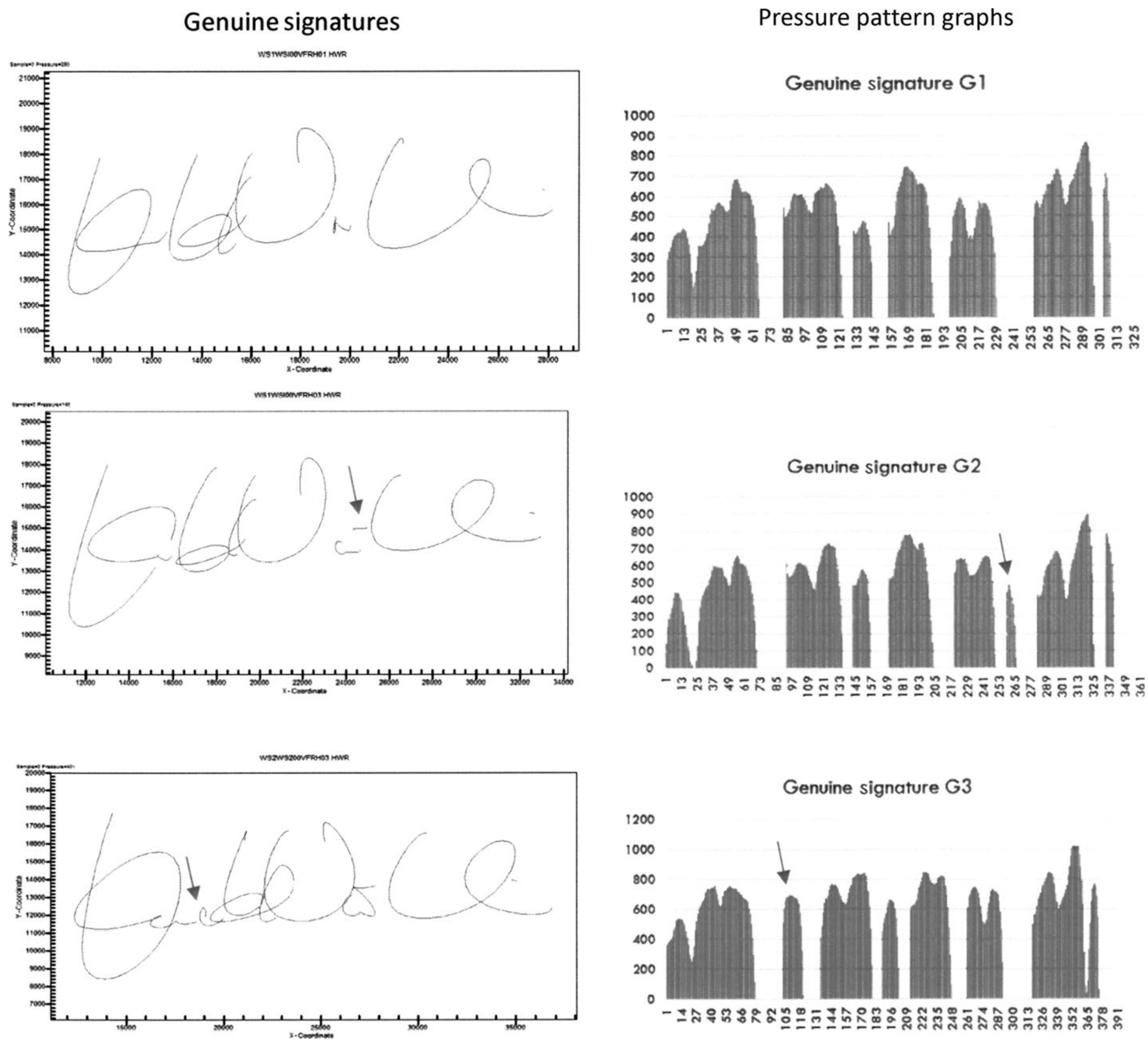

FIG. 4—*Natural variation displayed in signatures of the same signatory and their pressure pattern graphs.*

results are summarized in Table 3. A total of 782 pairs of the genuine signatures accounted for 95.4% have an rPA > 0.7 and 80% have an rPA > 0.8.

TABLE 2—*Summation of pen pressure of each peak of the three genuine signatures.*

Peak No.	Σp_1 for Signature G1	Σp_2 for Signature G2 (Ignore Peak 10)	Σp_3 for Signature G3 (Ignore Peak 4)
1	7011	6060	10059
2	10899	12489	16031
3	12548	11250	19498
4	11361	12463	14902
5	12194	13078	17077
6	5549	7103	8373
7	13393	15796	16464
8	5445	6138	9385
9	6995	8986	10610
10	8897	9548	9906
11	14522	13026	16504
12	14103	14762	18926
13	2978	4780	5910

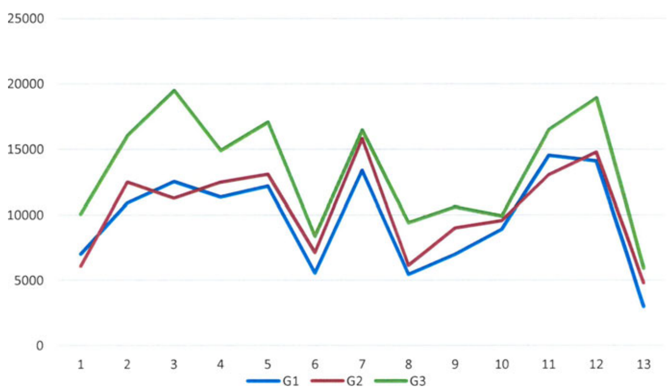

FIG. 5—*Graph of summation of pen pressure of each peak versus the peak number of the three genuine signatures. [Color figure can be viewed at wileyonlinelibrary.com]*

Simulated Forgery

Three document examiners simulated a total of 38 initials and signatures. Among these forged initials and signatures, 34 of them were executed with a longer time; 1.25–3.28 times of the corresponding genuine signatures with the longest execution time. Three showed comparable execution time and one showed shorter execution time. The longer in execution time in general also agreed with the findings reported by Mohammed et al. (18).

A forged signature S1 and the two genuine signatures G1 and G2 of relatively complicated design are shown in Fig. 6. The forged signature and the genuine specimens displayed similar pictorial design. From the images of these signatures, they appeared to be fluently written with smooth turnings and connection of strokes. However, the Pearson's correlation coefficients rPA for the comparison of the pressure pattern of the forged signature S1 with those of the genuine signature G1 and G2 were 0.26 and 0.31, respectively, whereas the rPA for the two genuine signatures was 0.95.

A forged initial Si1 and two genuine specimens Gi1 and Gi2 of simple design are shown in Fig. 7. They resembled each other in pictorial appearance. Both the forged and genuine initials were written in one continuous stroke, displaying smooth turnings, and no sign of hesitation was observed from the images. The pressure patterns of the forged and genuine initials are also shown in Fig. 7. The Pearson's correlation coefficients rPA for the comparison of the pressure pattern of the forged initial Si1 with those of the genuine specimens, Gi1 and Gi2, were 0.25 and 0.24, respectively, whereas the rPA for the two genuine signatures was 0.92.

However, another forged initial Si2 and the corresponding genuine specimens Gi3 and Gi4 of simple design written in a stroke-by-stroke manner are illustrated in Fig. 8. As the initials were written in a stroke-by-stroke manner, pen lifts were found after every stroke was finished and the pressure patterns of the simulated and genuine specimens displayed the same number of peaks as the initials were written with same number of strokes. The Pearson's correlation coefficients rPA for the comparison of the pressure pattern of the forged initial Si2 with those of the genuine specimens, Gi3 and Gi4, were 0.81 and 0.74,

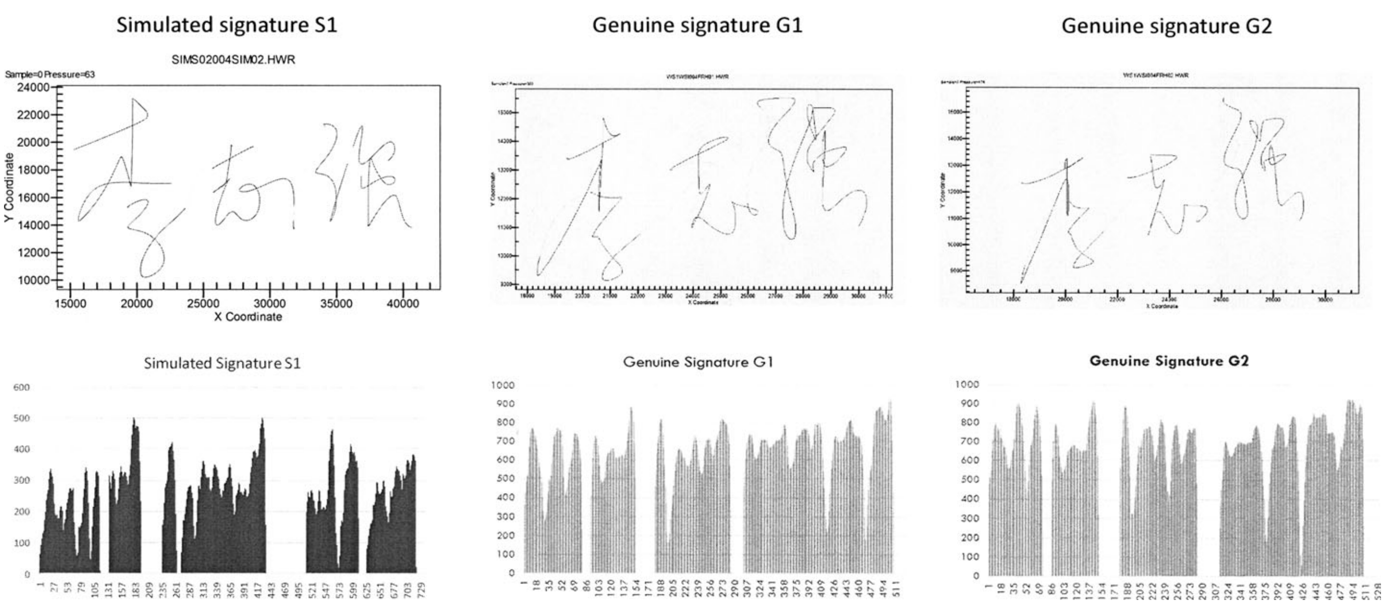

FIG. 6—*Images of a simulated signature and two genuine signatures; and their corresponding pressure pattern graphs.*

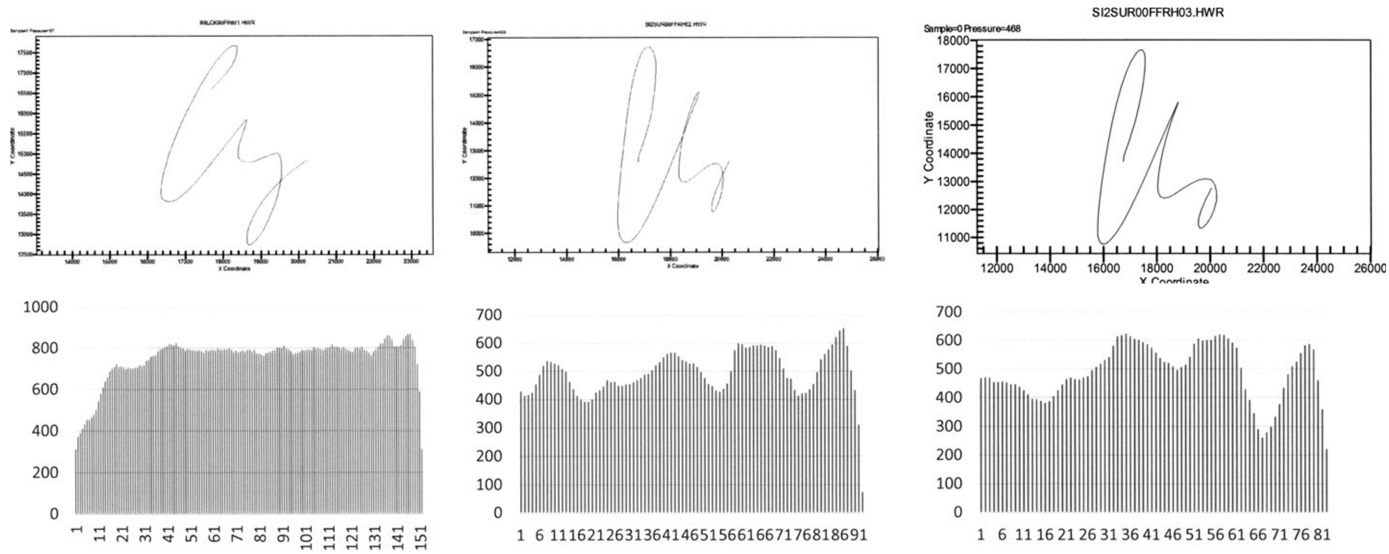

FIG. 7—*Images of a simulated initial and two genuine initials; and their corresponding pressure pattern graphs.*

TABLE 3—*Results of the Pearson's correlation coefficient of the comparison between the 48 sets of signature/initial specimens.*

rPA	No of Pairs of Signatures/Initials	%
>0.9	381	46.5
0.8 < X < 0.9	275	33.5
0.7 < X < 0.8	126	15.4
0.6 < V < 0.7	27	3.3
<0.6	11	1.3

respectively, whereas the rPA for the two genuine initials, Gi3 and Gi4, was 0.93.

Pearson's correlation coefficient was used in the comparison of 23 initials and signatures with each of the corresponding genuine specimens. Table 4 summarizes the results of a total of 139 pair comparisons that were conducted. A rPA < 0.6 was obtained for the comparison of 20 simulated initials and signatures with the corresponding control specimens. Only two initials and one signature of simple design either written in a stroke-by-stroke manner or contain simple wavy stroke gave rPA of 0.76–0.81.

The other 15 simulated signatures and initials showed obvious differences in pressure patterns, lacking well-defined peaks as exemplified in the genuine specimens. In addition, they were written with a longer execution time; difference in pen lift and sequence of writing were also found in some of these simulated signatures and initials.

Figure 9 illustrates an example using the *x*-coordinates of the signatures to distinguish different sequence of writing in two signatures. Obvious differences were found in the pressure pattern graphs of the genuine and simulated signatures. The genuine signature was written with a characteristic sequence from right to left, whereas the forged signature was written in a usual left to right manner, which is consistent with the *x*-coordinate versus time graphs. The *x*-coordinates of the genuine signature were

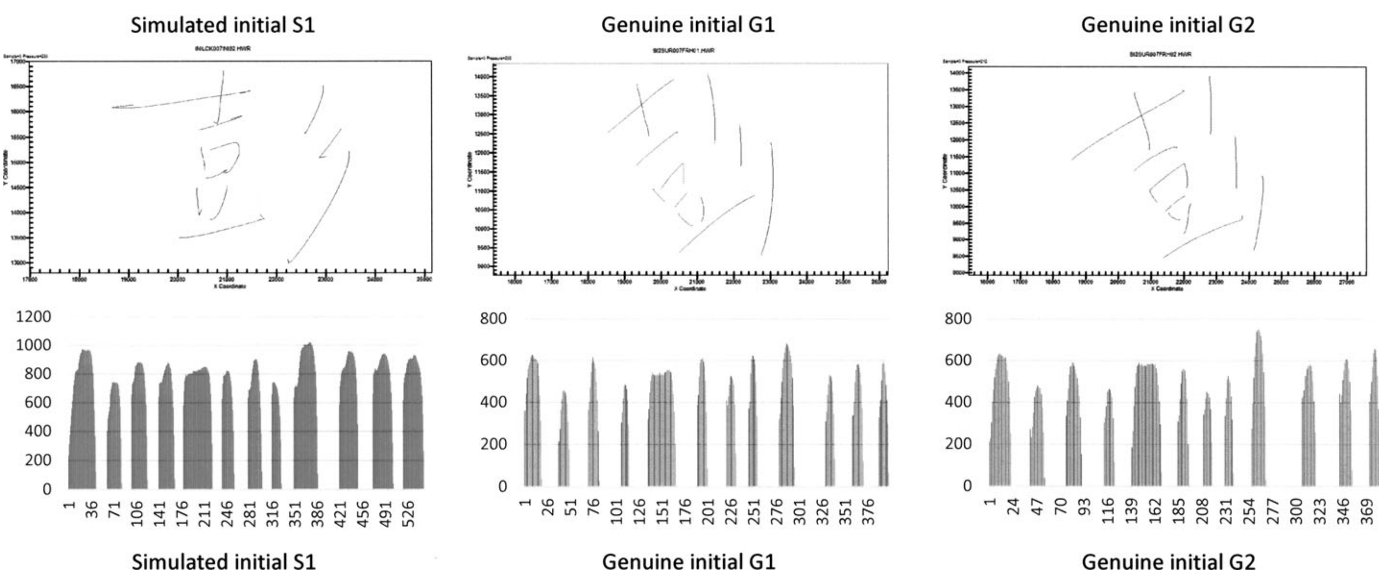

FIG. 8—*Images of a simulated initial and two genuine initials; and their corresponding pressure pattern graphs.*

decreasing, whereas those of the simulated signature were increasing.

Traced Forgery

Three document examiners traced a total of 21 initials and signatures. As illustrated in Fig. 10, the pressure pattern of the traced forgery displayed relatively even pen pressure and lacked well-defined peaks as exemplified in the genuine signatures. It is expected that the forgers applied a heavy pen pressure in the tracing act; however, both heavier and lighter pen pressure were observed in the traced forgeries. Nevertheless, the execution time of the traced forgeries was found to be longer than the genuine signatures, 2.02–6.43 times the corresponding genuine signature with the longest execution time.

TABLE 4—*Results of the Pearson's correlation coefficient of the comparison between the 23 simulated signature/initial with the corresponding genuine specimens.*

rPA	No of Pairs of Signatures/Initials	%
<0.0	24	17.2
0.0 < X < 0.2	19	13.7
0.2 < X < 0.4	52	37.4
0.4 < V < 0.6	29	20.9
>0.6	15	10.8

Discussion

Pen pressure is the amount of pressure exerted on the pen point and is the result of the rhythmical contraction and relaxation of muscles during the act of writing. Osborn stated the importance of pen pressure in signature identification. He expressed that "a delicate, inconspicuous, and almost wholly unconscious variation in line quality, weight of stroke, location of emphasis, smoothness of line and manual skill that has high

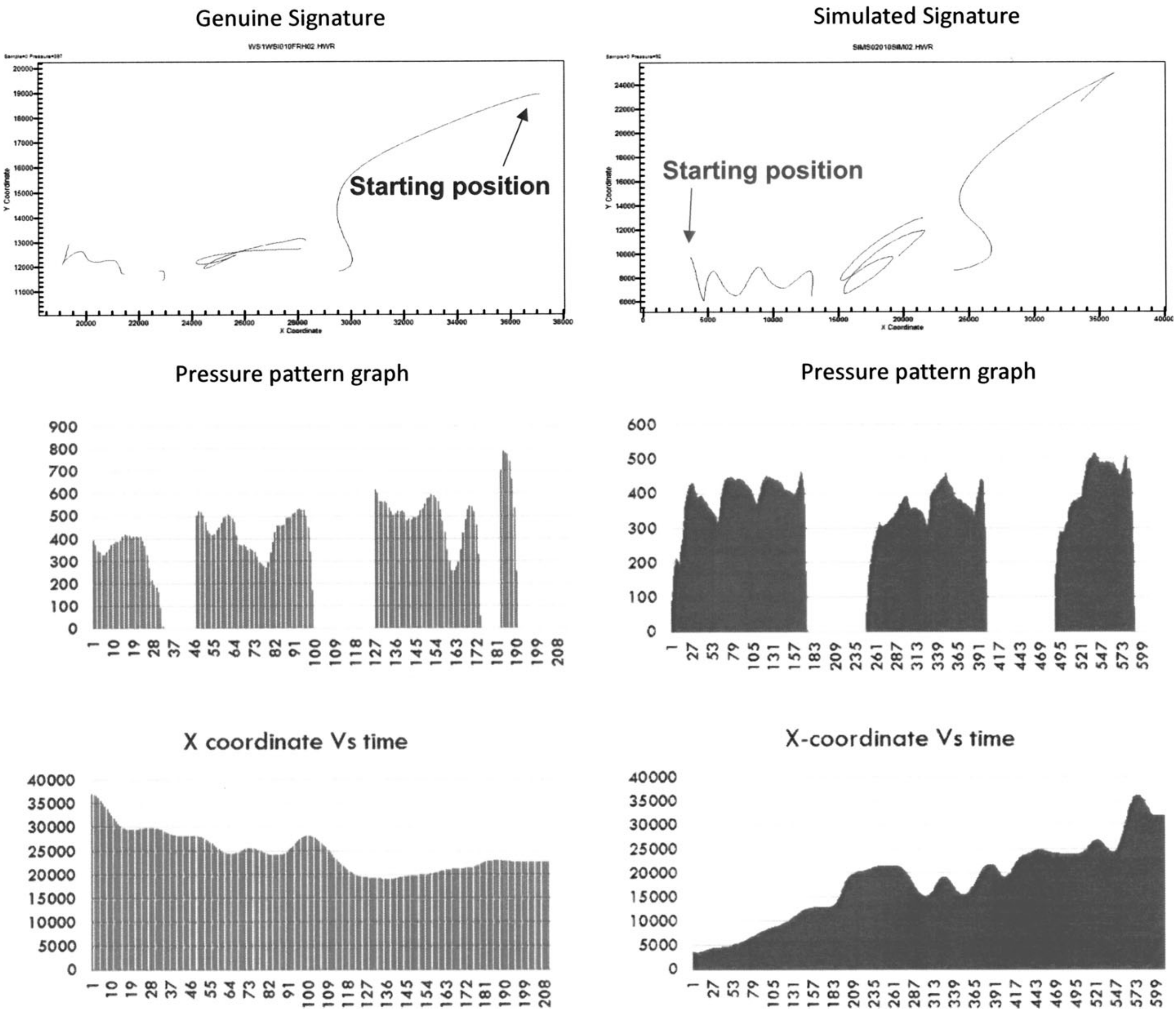

FIG. 9—*The images, the pressure pattern graphs and the graph of* x-coordinate *versus time of a genuine and simulated signatures.*

identifying value. As shown in the "quality of line," and especially the location and character of emphasis or unconscious shading, the variation in this feature is one of the most important evidences of genuineness and forgery" (21).

The variations in pen pressure are usually manifested in the contrast of darkness and lightness of the ink stroke. However, the nature of the ink and the absorbance of the paper surface may hinder the examination. In addition, the pen pressure pattern of the entire writing could hardly been visualized by tradition photographic technique. The pressure measuring device used in this study offers the advantage of showing the pen pressure pattern of the entire signature in a graphical form which could be easily be visualized and compared.

In this study, Pearson's correlation coefficient was used to compare the data of the pen pressure patterns. From the results of 820 pair comparisons of the 48 sets of genuine signatures, a high degree of matching was found in which 95.4% (782 pairs) and 80% (656 pairs) had a rPA > 0.7 and rPA > 0.8, respectively. In addition, the establishment of the relationship between the stoke segments and peaks in the pressure patterns graph as in Fig. 4 allows the comparison of signatures with variation in structures.

Under normal circumstance, it may be difficult for a document examiner to offer an opinion on the authorship of questioned signature and initial with simple design, particularly copied signature and initial as characteristic writing features that could be depicted from the specimens would be very limited. The approach suggested in this study does not only fit for the comparison of signatures of complicated design, it may also assist in the comparison of initials of simple design as illustrated in Fig. 7.

In the comparison of the 23 forged signatures with their corresponding control signatures, 20 of them (89.2% of pairs) have rPA values < 0.6, showing a lower degree of matching when compared with the results of the genuine signatures. From the results in this study, a combination of (i) a pressure pattern with a relatively even pressure and lack of well-defined peaks, (ii) a much longer execution time, and (iii) a lower rPA value is strong indication of simulated forgery.

The application of Pearson's correlation coefficient in determining the matching between variables has been well established in a number of areas. The mathematical approach is easy to understand, and the tools are readily available. In this study, the treatment of the pen pressure data using Pearson's correlation coefficient provides an objective means to determine the degree of matching between two signatures, which could be used for the identification and elimination of common authorship.

Limitations

The major limitation of the device used in this study is that it cannot show the writers what they wrote on the writing surface. Besides, a long examination time would be required in the establishing the relationship between stroke segments and peaks. The mathematical approach still encounters the difficulties in examining (i) forged signatures with simple pattern, particularly those

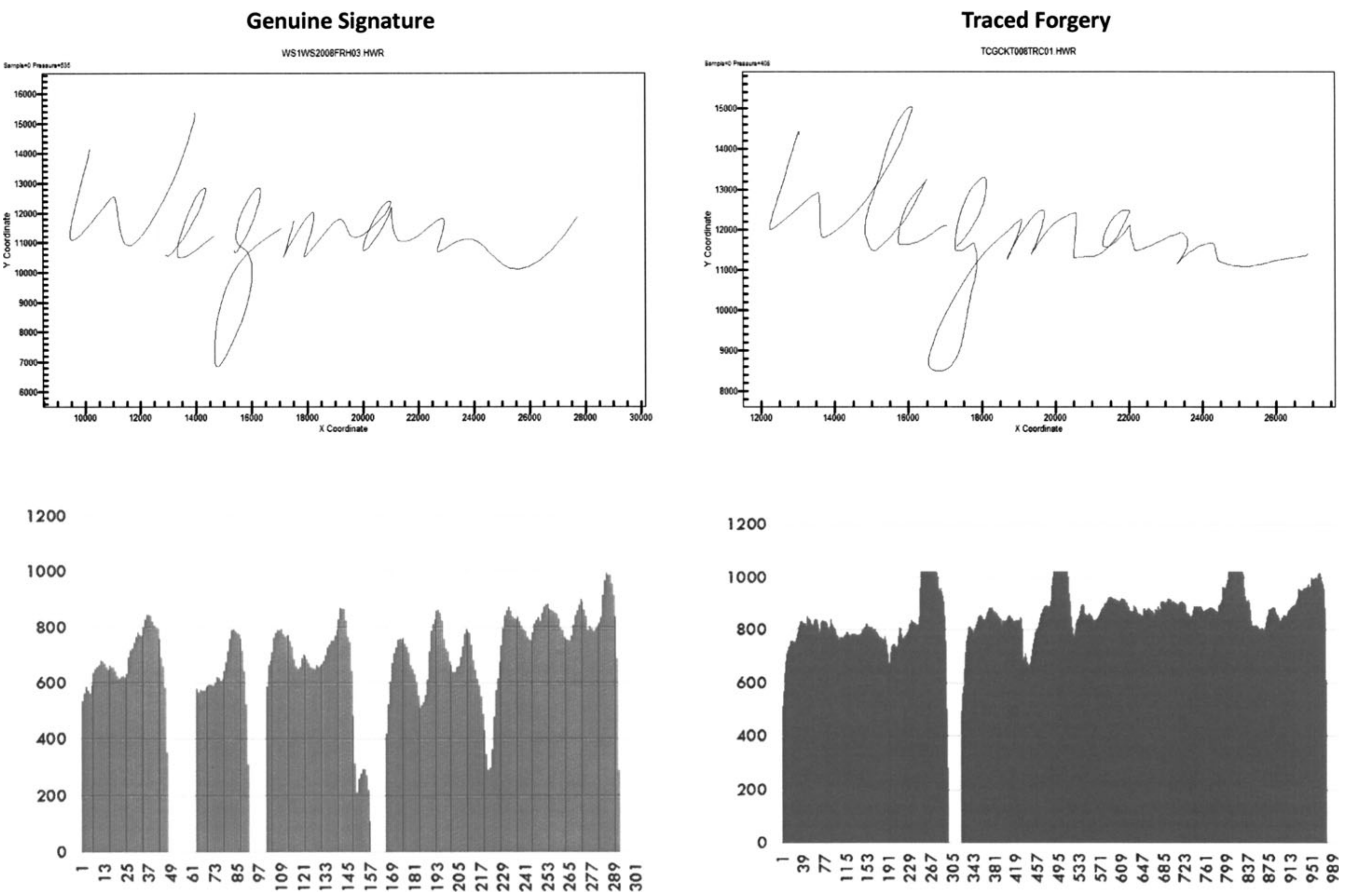

FIG. 10—*Pressure pattern graphs of a genuine signature and a signature traced from the genuine signature.*

written in a stroke-by-stroke manner or simple writing movement and (ii) wide range of variation in signatures or lack of consistency in writing of poor penmanship. Last but not least, the device is for research purpose only and still not available for commercial activities.

Way Forward

As tablets have been used in many daily activities and digitized signatures would be the major source for signature comparison. With the advance in technology and the lowering in production cost, the incorporation of the software to the writing pad and the development of software for automated analyses would not be a difficult task. Normal course of business specimens and information relating to pen pressure, relative alignment, writing sequence, and movement would be readily available which could facilitate the examination of digitized signatures. The use of Pearson's correlation coefficient was found to be effective in comparing the pressure patterns of signatures, and it also provided an objective and quantitative mean which could be used to support the opinion offered in the examination of questioned signatures. The possibility of setting up matching and scoring criteria for identification and elimination of authorship could be further investigated.

Acknowledgements

The authors would like to record here their gratitude to Dr. Wai-mei SIN, the Government Chemist of Hong Kong Special Administrative Region, for her support and encouragement in this work.

References

1. Jain AK, Ross AA, Nanadakumar K. Introduction to biometrics. New York, NY: Springer, 2011.
2. Osborn AS, Wigmore JH. Questioned documents. 2nd edn. Albany, NY: Boyd Printing Co., 1929. Facsimile ed. Chicago, IL: Nelson-Hall, 1974.
3. Hilton O. Scientific examination of questioned documents. New York, NY: Elsevier Science Publishing Company Inc, 1982.
4. Harrison WR. Suspect documents their scientific examination. Reprint of 1958 ed. Praeger, NY. Chicago, IL: Nelson-Hall, 1981.
5. Huber R, Headrick A. Handwriting identification: facts and fundamentals. New York, NY: CRC Press, 1999.
6. Hilton O. Contrasting defects of simulated and genuine signature. Fingerprint Identification Magazine 1964;46(4):3–14.
7. Leung SC, Cheng YS, Fung HT, Poon NL. Forgery I – simulation. J Forensic Sci 1993;38:402–12.
8. Leung SC, Fung HT, Cheng YS, Poon NL. Forgery II – tracing. J Forensic Sci 1993;38:413–24.
9. Tytell PV. Pen pressure as an identifying characteristic of signatures: verification from the computer. J Am Soc Questioned Doc Examiners 1997;1(1):21–31.
10. Dawson GA, Lindblom BS. An evaluation of line quality in photocopied signatures. Sci Justice 1998;38:189–94.
11. Found B, Rogers DK. Investigating forensic document examiners' skill relating to opinion on photocopied signatures. Sci Justice 2005;45:199–206.
12. Fahmy MMM. Online handwritten signature verification system based on DWT features extraction and neural network classification. Ain Shams Eng J 2010;1:59–70.
13. Putz-Leszczynska J, Pacut A. Model approach to DTW signature verification using error signals. J Forensic Doc Examination 2012;22:41–54.
14. Liwicki M. Automatic signature verification: in depth investigation of novel features and different models. J Forensic Doc Examination 2012;22:25–39.
15. Parodi M, Gómez JC, Alewijnse L, Liwicki M. Online signature verification: automatic feature selection vs. FHE's choice. J Forensic Doc Examination 2014;24:5–19.
16. Parziale A, Fuschetto SG, Marcelli A. Modeling stability in on-line signatures. J Forensic Doc Examination 2014;24:37–46.
17. Houmani N, Garcia-Salicetti S, Dorizzi B. On measuring forgery quality in online signatures. Pattern Recogn 2012;45:1004–18.
18. Mohammed L, Found B, Caligiuri M, Rogers D. Dynamic characteristics of signatures: effects of writer style on genuine and simulated signatures. J Forensic Sci 2015;60:89–94.
19. Committee on Identifying the Needs of the Forensic Sciences Community, National Research Council. Strengthening forensic science in the United States: a path forward. Washington, DC: National Academies Press, 2009.
20. Koo I, Kim S, Zhang X. Comparative analysis of mass spectral matching-based compound identification in gas chromatography-mass spectrometry. J Chromatogr A 2013;1298:132–8.
21. Osborn AS. Questioned document problems. 2nd rev. edn. Montclair, NJ: Patterson Smith, 1991.

Additional information and reprint requests:
Chi-Keung Li, Ph.D.
Government Laboratory
Ho Man Tin Government Offices
88 Chung Hau Street
Kowloon, Hong Kong Special Administrative Region
People's Republic of China
E-mail: ckli@govtlab.gov.hk