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Fingerprint quality per individual finger type: A large-scale study on real operational data

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***Abstract*—Even though some initial works have shown on small sets of data that not all fingerprints present the same level of utility for recognition purposes, there is still insufficient data-supported evidence to understand the impact that finger type may have on fingerprint quality and, in turn, also on fingerprint comparison. The present work addresses this still under-researched topic, on a large-scale database of operational data containing 10-print impressions of over 18,000 subjects. The results show a noticeable difference in the quality level of fingerprints produced by each of the 10 fingers and also between the dominant and non-dominant hands. Based on these observations, several recommendations are made regarding: 1) the selection of fingers to be captured depending on the context of the application; 2) improvement in the usability of scanners and the capturing protocols; 3) improvement in the development, ergonomics and positioning of the acquisition devices; and 4) improvement of recognition algorithms by incorporating information on finger type and handedness.**

***Index Terms*—Fingerprint recognition, Biometric Quality, Slaps scanners, Large-Scale IT Systems, Handedness**

I. Introduction

"All fingerprints are equal, but some fingerprints are more equal than others[1]*"*

It is nowadays a well-established and accepted fact by the research and practitioners community, that quality of biometric samples is the primary factor impacting the accuracy and overall performance of biometric recognition systems.

Such a statement, which may seem far-fetched and bold at first sight to a newcomer, can be also directly derived from the definition of biometric quality established by the ISO/IEC 29794-1:2016 standard [1]. The ISO document defines quality as the "*degree to which a biometric sample fulfils specified requirements for a targeted application*". In essence, this definition means that biometric quality, for the targeted application of biometric recognition, can be understood as a predictor of how well a biometric sample will perform in terms of accuracy when used for recognition purposes in a given biometric system (or set of biometric systems). In other words, quality of a biometric sample, estimates the likelihood of achieving a correct comparison result when that sample is used within a recognition system.

As in many other areas related to biometrics performance, fingerprint is the biometric characteristic that has led the advancement of quality analysis and research. From the very inception of quality as a key area in biometrics, fingerprint has been at the forefront of the scientific progress, with a plethora of initiatives specifically targeting the study of fingerprint quality such as: dedicated conferences, international evaluations, standardisation initiatives, specific research publications or publicly funded projects.

Thanks to this large investment dedicated to fingerprint recognition, both from an economic and human resources perspective, an overwhelming amount of information has been produced, compiled in multiple different studies, reports and publications that have covered the topic of fingerprint quality from numerous complementary perspectives [2]. As a result, nowadays we have a very good understanding, among other areas, of the different factors that have an impact on fingerprint image quality [3], we have standardised system-agnostic quality measures [4], we know how fingerprint image quality evolves with age [5], what sensing technologies tend to produce better quality samples [6], how quality information can be integrated in recognition algorithms in order to improve accuracy [7] or how it can be exploited to increase the security of systems against attacks [8].

However, the vast majority of these unarguably valuable works, do not make any distinction among individual fingers in terms of quality. Only a few early studies, carried out on small sets of data, consider the analysis of quality and recognition accuracy from each finger type[2]. Furthermore, except for three of these research publications [9]–[11], in general, existing literature only addresses the topic as a by-result of experimental evaluations with a different main focus (see Sect. II). However, even if carried out on small sets of data captured *ad-hoc* in laboratory conditions, all these pioneer studies already point out to the possibility that the quality level and performance of the images produced by each individual finger may vary quite significantly.

Building upon the findings of these preliminary publications, in the present paper we conduct the first large-scale

[1]Paraphrase of the famous quote "*all animals are equal, but some animals are more equal than others*" from George Orwell's allegorical novel "Animal farm", 1945.

[2]In the present work, *finger type* refers to each of the five digits of the hand: thumb, index, middle, ring and little fingers

study of fingerprint quality based on individual fingers, carried out on a large database of real operational data. The objective of the analysis is to determine if, based on the current most commonly deployed state of the art acquisition devices (i.e., 500dpi touch-based optical scanners), there is a difference in the quality level of each finger. That is, we want to give an answer to the question: are all fingers born equal (in terms of quality)? Or put in another way, should all fingerprints be treated the same in terms of fingerprint recognition? Do all fingers produce images that present the same discrimination potential? Are fingerprint samples produced by all fingers equally suited for personal authentication? Do all fingerprint samples possess the same amount of discriminative information independently of the finger that produced them?

The analysis and results presented in the paper can bring yet further insight into the key area of fingerprint quality from a new perspective, not considered in research publications to date, bridging one of the few gaps that still exist in the field. As such, the conclusions drawn from it, can be of big value to different actors involved in the design, development and deployment of fingerprint-based operational systems.

II. Related Works

As mentioned in the introduction, few works in the literature have addressed the topic of fingerprint image quality and performance, based on each individual finger. Furthermore, most of these studies focus on areas related to fingerprint recognition different to quality assessment, and have only marginally considered the questions addressed in this paper.

However, even if it is not their main focus, but rather a by-product of their primary research objectives, all these preliminary publications point out to some interesting trends regarding the individual quality of fingerprints. The observations and conclusions extracted in those analyses have been extracted on some small sets of data captured *ad-hoc* in laboratory conditions for the specific purpose of the experimental evaluations and, therefore, their statistical significance is somewhat limited and should be further confirmed (or corrected) on large-scale datasets containing real operational samples, which is one of the motivations of the present paper.

Out of the three most relevant works from the state of the art, related to the current piece of research, two of them were both published in 2010. In the first of these studies [9], researchers from the Gjovik University analysed the influence of finger types on fingerprint recognition performance, over a database containing all 10 fingers of 100 subjects. Fingerprints were captured individually (not slaps impressions) using six different scanners, five touch-based and one touchless. Their analysis confirmed for the first time following a rigorous scientific protocol, the general claim that was commonly made to that date without a solid experimental basis, regarding the lesser accuracy of the little finger for recognition tasks. In addition, the study gave some further preliminary insight, pointing out that the best performance was obtained with the thumb and index fingers, with a very noticeable drop in accuracy between those two best fingers and the little finger.

In the second of the 2010 studies, the authors examine how fingerprint recognition systems can balance the speed of single-print systems with the robustness of ten-print systems by using a combination of fingers [10]. For this objective, a database containing images of all 10 fingers from 70 subjects was used. Fingerprints were acquired one by one (not slaps) using an optical touch-based scanner. It was found that the thumb, index, and middle fingers of both hands presented the highest quality scores and were, accordingly, also the fingers providing the best accuracy in recognition tasks.

The last study from the state of the art covering, among other aspects related to fingerprint recognition, the topic addressed in the present work, was published very recently, in 2022, by researchers from the University of Salzburg [11]. The paper presents the new publicly available PLUS-MSL-FP dataset, which contains fingerprint data from all ten digits, provided by 59 subjects over a time span of two years, using 10 different single-finger flat sensors (four optical, 5 capacitive and 1 thermal). As part of their initial assessment of the database, the authors give the mean, median, and standard deviation of the NFIQ2 values for all the images, per hand and per finger type. While the left and right hand provide almost the exact same quality results, as in the 2010 studies, it can be seen that thumbs tend to produce the best quality, while the ring and little fingers produce the lowest values.

Therefore, the three main studies summarised above, coincide in their conclusions on the quality and accuracy of finger types. They all showed that the little fingers present the worst performance of all fingers, while the best is reached using the thumbs and indexes. These observations were, to a large extent, further reinforced in two publications by the US NIST: a Technical Report from 2008 were the authors studied the usability of ten-print finger scanners over a dataset of 126 individuals [12]; and a Short Note from 2018 where NIST announced the public release of a new fingerprint database, NIST 300, consisting of both flat and rolled fingerprints coming from paper-and-ink 10-print records provided by the FBI, acquired from 888 different subjects [13].

We believe that it is important to highlight once more that all these works were performed on restricted sets of data not captured in real operational conditions and, therefore, their final observations, while valid and valuable, should be understood as tendencies rather than as statistically data-supported solid conclusions.

III. Experimental Database

The database used for the present study was captured in the span of three months, between March and May 2022, in the context of a pilot project carried out jointly between the Swedish Migration Agency (Migrationsverket) and eu-LISA. The collaborative effort was focused on the improvement of processes involved in the issuing and control of VISAs for non-EU citizens entering the Schengen area and, in particular, on the testing of tools for biometric quality assessment. The original database owned and processed by the Swedish Migration Agency contains a total 18,164 different 10-print digital records produced by as many subjects, that is, it comprises a total 181,640 fingerprint samples. As explained at the end of this section, eu-LISA did not have direct access to the fingerprint samples, but only to anonymised meta-data derived from the processing, by the Swedish Migration Agency, of the original database.

All subjects in the dataset are above 12 years old. Individuals come from 34 different non-EU countries around the world. Fingerprints were captured in 115 different locations with specific designated stations for VISA issuing purposes. Therefore, fingerprints were captured mostly in office-like scenarios with controlled environment conditions, and the process was conducted by operators with experience and instruction in the field of fingerprint acquisition.

All fingerprints were captured using the same FBI-certified touch-based 500 dpi optical scanner (Cross Match Patrol ID). All fingerprint images are flat. For each 10-print record three different images were captured, following the typical sequence 4-4-2, that is: slap of the right hand (all four fingers acquired simultaneously), slap of the left hand (all four fingers acquired simultaneously) and lastly the two thumbs. In case of low quality, fingerprints were reacquired up to three times, and the best individual quality score for each finger was kept.

Due to data protection reasons, for the experimental evaluation eu-LISA did not have direct access to the fingerprint images, which were at all time kept and processed by the Swedish authorities, owners of the data. eu-LISA only received anonymised excel files where each subject included in the database was assigned an ID-code only linkable to his/her real identity for the Swedish authorities. For each individual, the relevant meta-data available in the excel files which was used in the experimental analysis was: 1) finger type (left or right; thumb, index, middle, ring or little); 2) NFIQ-2 value extracted during the acquisition process by the Swedish Migration Agency.

IV. Results and Analysis

For the experimental evaluation, the NFIQ-2 v2.0 was used as tool to assess quality (freely available from [14]). The NFIQ-2 software is a system-agnostic fingerprint quality measure which is formally recognized as a reference implementation of the normative metrics presented in the ISO/IEC 29794-4:2017 standard. The code was initially developed in 2004 (NFIQ-1) as an initiative of NIST in respond to the need of reliable quality assessment tools dissociated from specific vendors. Advances in fingerprint technology since 2004 made necessary an update to NFIQ-1. As such, development of NFIQ-2 was initiated in 2011 as collaboration between NIST and Germany's Federal Office for Information Security (BSI) and Federal Criminal Police Office (BKA), as well as research and development entities MITRE, Fraunhofer IGD, Hochschule Darmstadt, and Secunet. Currently the project is updated and maintained by the ISO SC 37 Working Group 3.

The NFIQ-2 quality measure has been independently evaluated in numerous occasions, showing very good performance across recognition systems, and has nowadays been adopted

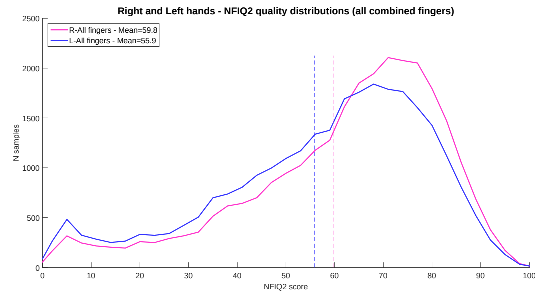

Fig. 1. NFIQ-2 quality distributions of all fingers in the database by hand (right hand is shown in pink and left hand is shown in blue). The vertical dotted lines show the mean value of each distribution.

by the biometric community as the *de facto* benchmarking standard. The current version of NFIQ-2 is trained on flat fingerprints of 500 dpi resolution, captured with optical devices, that is, the same category of fingerprints contained in the experimental database used in the present work.

As explained in Sect. III, fingerprint images in the original database were processed at the time of acquisition by the data owners and their NFIQ-2 value extracted and made available to eu-LISA through anonymised excel files. The NFIQ-2 scores were further analysed by eu-LISA researchers with regard to: 1) the hand (right/left) that produced them; 2) and the specific finger type for each hand individually. Fig. 1 shows the NFIQ-2 quality distribution for all the fingers combined of the left hand (blue) and of the right hand (pink).

OBSERVATION 1: from Fig. 1 it can be observed that the right hand consistently provides better quality fingerprint images than the left hand.

HYPOTHESIS 1: our explanation to this first observation is related to the handedness of human beings. It is estimated that around 90% of the world population is right-handed. As such, it is expected that most individuals (those right-handed) are more skilled to interact with the acquisition scanner using the right hand (their dominant hand) and, therefore, to provide better quality fingerprints.

The effects of handedness on fingerprint quality and performance was already considered in a 2010 work carried out on a database of 40 subjects, evenly distributed between right- and left-handed [15], and also in [11] over a database of 59 subjects of unknown handedness. In those studies, probably due to the limited number of subjects included in the databases, results did not show any conclusive trends regarding the impact of handedness on fingerprint performance. The present findings bring further insight into the final observations of [11], [15] and support the assumption that there is a difference in accuracy between the use of the dominant and non-dominant hand of subjects for fingerprint recognition. However, such an initial observation should still be confirmed on a large-enough fingerprint database including handedness information, ideally with a balance distribution of subjects in terms of their dominant hand.

In Figs. 2 and 3 we present, respectively, the quality

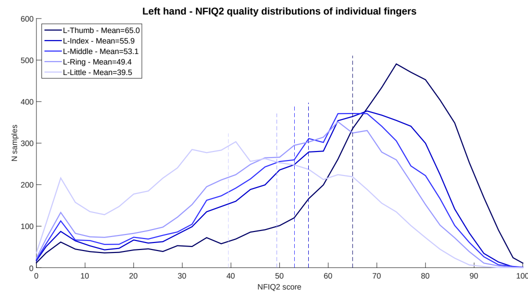

Fig. 2. NFIQ-2 quality distributions of all individual fingers in the database corresponding to the left hand. The vertical dotted lines show the mean value of each distribution.

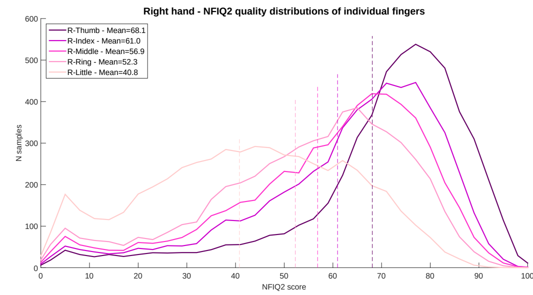

Fig. 3. NFIQ-2 quality distributions of all individual fingers in the database corresponding to the right hand. The vertical dotted lines show the mean value of each distribution.

distributions for each individual finger of the left and right hand. The respective box-plots of all 10 distributions are depicted following the natural order of the fingers of both hands in Fig. 4. On each box, the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' marker symbol.

OBSERVATION 2: from these figures it can be seen that the quality of fingerprints differs quite significantly depending on the finger type. Fingers, ordered from higher to lower quality of their produced fingerprints are: thumb, index, middle, ring and little. This is consistent across both hands. This order follows the natural order of fingers in the hand.

This observation 2 is consistent with the results obtained in [11] over a database of 59 subjects.

OBSERVATION 3. Not only the quantitative quality values change, but also the variability (height of the boxes in Fig. 4) of these values increases following the same finger order specified in observation 2. That is, the lower the quality values produced by finger type, the more inconsistent these values are. In other words, individuals find more difficult to produce consistent quality fingerprints the further away we move from the index in the finger order.

This observation 3 does not coincide with the results obtained in [11], where the standard deviation of the NFIQ-2 values of all fingers was very similar, with not appreciable trend.

OBSERVATION 4. The most noticeable differences among all fingers are: 1) the low quality produced by the little finger compared to all other four digits, which also presents clearly the largest variability in the values. 2) The higher quality level produced by the thumbs, captured independently, compared to all four slaps fingers (captured simultaneously); the thumbs also produce the most consistent quality scores.

This observation 4 supports the initial results obtained in [11].

HYPOTHESIS 2: It has been hypothesised in the past that the lower utility of the little finger could be due to its smaller size and, therefore, to encompassing less discriminative information from a natural point of view. However, the results reached in this study show that both the middle and ring fingers also provide lower quality than the index, while presenting, on average, a larger surface. It should also be taken into account that for the four slap-fingers quality values decrease and quality variability increases following exactly their natural order. These results, together with the fact that the two thumbs, which are the digits captured individually, present clearly the highest quality level and the lowest quality variability, support in our view a different hypothesis. Based on observations 2, 3 and 4, contrary to the size-based assumption, our explanation is that the difference in quality among fingers is *mostly* due, not to the distinctive information contained in natural fingerprints ("*character*" definition of quality in ISO/IEC 29794-1:2016), but to the way in which these are translated to the digital domain by acquisition scanners ("*fidelity*" definition of quality in ISO/IEC 29794-1:2016). That is, in their natural state, it is likely that all fingerprints present a similar amount of discriminative information, however, due to the ergonomics/usability of slap scanners, this information is better captured for some fingers.

Touch-based slap acquisition devices require the user to press all four fingers contemporarily against a flat platen, following a straight line from the subject. From an anatomical perspective, due to the limitations of the wrist and finger joints, this task is easier to perform with the index finger, and becomes increasingly less comfortable for the rest of the fingers. The result is a good interaction of the index finger with the scanner, that worsens successively for the other fingers. This increasing difficulty in the correct use of the scanner entails that quality values become lower and more inconsistent.

Another factor to be taken into account is that, when capturing all four fingers simultaneously, it is more difficult for the subject to control the amount of pressure applied to each single one of them separately. It has been pointed out in different works that, when using touch-based scanners, the pressure applied against the platen is one of the key parameters that determines the final quality level obtained for the resulting fingerprint images [16].

Following a similar rationale as above, since thumbs are acquired separately, subjects are capable of placing them correctly on the platen, and have better control over the pressure

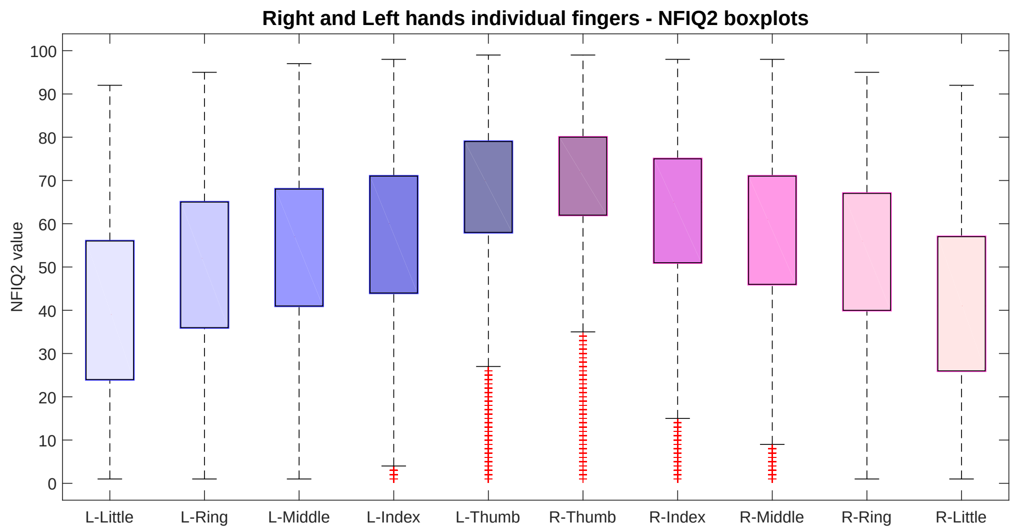

Fig. 4. Box-plots corresponding to the NFIQ-2 quality distributions shown in Figs. 2 and Figs. 3. For clarity, the box-plots follow the natural order of the fingers of both hands. The box-plots corresponding to fingers of the left had are depicted in shades of blues, while those corresponding to fingers of the right hand are shown in shades of pink.

applied to each of them, independently of the rest of fingers, resulting in high quality images. These results confirm, on a statistically significant database, what was initially pointed out by the three main works cited in Sect. II [9]–[11].

V. Conclusions

Given the paramount importance of quality in biometrics, a very significant amount of effort has been dedicated from all stakeholders in the field (researchers, practitioners, users, developers, vendors) to study the main factors that have an impact on the quality of different biometric characteristics. In particular, as happens in many other areas related to biometrics, fingerprints stand out as probably the biometric trait where the largest amount of research and information has been generated. In fact, the big investment made in fingerprint quality assessment, has paved the way for other biometric characteristics to get the support required to reach a similar level of development in terms of understanding of quality.

However, even if undeniable significant progress has been achieved in fingerprint quality analysis, there are still areas where further research needs to be performed in order to confirm or complement some preliminary observations that have been made on statistically limited sets of data. The present paper is a contribution to bring further insight into the field and to bridge some of these still existing gaps.

In particular, the present work is focused on determining the impact that each individual finger type has on the quality and overall performance of fingerprints in automated recognition systems. The results reached by the experimental evaluation can lead to practical decisions for the improvement on the use and deployment of this technology. In particular, the next concrete observations and actions can be defined based on the observations extracted from the results of the paper:

- The dominant hand of a subject is expected to produce fingerprints of higher quality.
- Not all fingers provide the same quality level.
- Based on the results, it would be worth testing if fingerprints captured individually present a higher quality level than fingerprints segmented from slap images, especially for the ring and little fingers. Such an initial assumption is based on the fact that if each finger interacts with the capturing device independently of the other fingers, it would give the subject better control over the process and, in turn, it would likely improve the quality of fingerprints. It should be noted that the results presented in [11] do not support the hypothesis made in the present work regarding the potential improvement in quality for single-finger scanners compared to slaps-scanners. That research paper made the analysis over a database containing all 10-fingers data of 59 subjects captured with 10 different single-finger sensors, and the same quality differences seen in the present study among finger-types was observed. However, we believe that to finally confirm or reject our hypothesis, further analysis on a large database of individually captured fingerprints still needs to be performed.
- For some specific applications it may not possible to acquire all 10 fingers, or it may be decided not to do it due to different constraints (e.g., restricted acquisition time). In these cases where an *a-priori* decision must be taken regarding which individual fingers to acquire, priority should be given to, in this order: thumb, index, middle, ring and little fingers.
- Recognition algorithms correlated to NFIQ-2 utility predictions, can also exploit this *a-priori* knowledge regarding the expected quality of fingerprints according to the

finger that produced them. For instance, specific score-level fusion strategies could be designed in order to give a higher weight in the final comparison outcome to those fingers that are known to provide better quality [7]. In addition, different processing algorithms could be expressly developed for those fingers that generally produce lower quality samples, especially for the little fingers, in order to extract from them all their discriminative information.
- Further research is required on the ergonomics and usability of current slaps touch-based optical scanners. While their performance is very high, it could still be improved to better acquire the ring and little fingers. This could be accomplished, for instance, using not a flat platen, but a slightly curved one, for example in the shape of a dome (or the top segment of a half sphere). Another possibility would be to change the angle of the flat platen, not to be perpendicular to the body, but to capture the fingers following the natural angle formed at the elbow by the arm and the forearm when it is comfortable rested on a desk or when the hand is placed in front of the chest.

The results reached in the present work also complement those presented in the NIST Technical Report that was published following the Fingerprint Vendor Technology Evaluation (FTVE) carried out in 2014 [17], where NIST assessed under different scenarios fingerprint recognition systems developed by 18 world-wide leading vendors. We highlight here two of the conclusions drawn from the FTVE large-scale assessment by NIST researchers, as they are related and of special relevance to the present study: 1) the right slap outperformed the left slap and the right index outperformed the left index. This is further corroborated by the handedness observation reached in the present work, that is, that the dominant hand is expected to produce, on average, better quality than the non-dominant one. 2) Interestingly, the recognition results reached in FTVE using both the right and left fingers together outperformed the results obtained using only the right slap or the left slap on their own. As the authors expressed in the report, they could not give a final fact-based explanation for this counterintuitive observation where, consistently among all systems tested, only two fingers (indexes) reached better results than all four fingers of a slap. The present work may have finally provided an answer to this anomaly: using the two indexes implies that recognition is based on the two best quality fingerprints, while when using a slap, although more fingerprints are involved, they are of lesser quality (especially the ring and little fingers) which may not only not contribute to comparison accuracy, but hinder it.

The most extended assumption to this point, was that the difference in accuracy/quality among fingers, especially the little one, was due to diverse *character* (as defined in the ISO/IEC 29794-1:2016), mainly coming from the smaller size of some fingers (that therefore present less discriminative information). However, the results reached in the present study over a large operational set of data, suggest and support the hypothesis that the divergence in *utility* among fingers should probably not be put down mainly to an inherent difference in character but rather, to an inconsistency in the *fidelity* in which fingers are translated to their digital form by current touch-based slap scanners.

Therefore, rather than simply excluding some fingers from the recognition process (i.e., typically the little finger), it could be a better approach to further invest in improving the ergonomics and usability of touch-based scanners for the acquisition of slaps impressions, in order to reduce the gap between the initial natural character and the final digital utility of fingerprint samples. Additionally, specific processing algorithms could be developed in order to better extract the discriminative information from the more problematic fingers; acquisition protocols could be improved (e.g., placement of scanners); and a better understanding of the technology by operators and users would eventually also help to improve recognition results (which highlights the importance of technology-related training and communication).

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