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TypeNet: Deep Learning Keystroke Biometrics

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Abstract—We study the performance of Long Short-Term Memory networks for keystroke biometric authentication at large scale in free-text scenarios. For this we introduce TypeNet, a Recurrent Neural Network (RNN) trained with a moderate number of keystrokes per identity. We evaluate different learning approaches depending on the loss function (softmax, contrastive, and triplet loss), number of gallery samples, length of the keystroke sequences, and device type (physical vs touchscreen keyboard). With 5 gallery sequences and test sequences of length 50, TypeNet achieves state-of-the-art keystroke biometric authentication performance with an Equal Error Rate of 2.2% and 9.2% for physical and touchscreen keyboards, respectively, significantly outperforming previous approaches. Our experiments demonstrate a moderate increase in error with up to 100,000 subjects, demonstrating the potential of TypeNet to operate at an Internet scale. We utilize two Aalto University keystroke databases, one captured on physical keyboards and the second on mobile devices (touchscreen keyboards). To the best of our knowledge, both databases are the largest existing free-text keystroke databases available for research with more than 136 million keystrokes from 168,000 subjects in physical keyboards, and 60,000 subjects with more than 63 million keystrokes acquired on mobile touchscreens.

I. INTRODUCTION

Keystroke dynamics is a behavioral biometric trait aimed at recognizing individuals based on their typing habits. The velocity of pressing and releasing different keys [1], the hand postures during typing [2], and the pressure exerted when pressing a key [3] are some of the features taken into account by keystroke biometric algorithms aimed to discriminate among subjects. Although keystroke biometrics suffer high intra-class variability for person recognition, especially in free-text scenarios (i.e. the input text typed is not fixed between enrollment and testing), the ubiquity of keyboards as a method of text entry makes keystroke dynamics a near universal modality to authenticate subjects on the Internet.

Text entry is prevalent in day-to-day applications: unlocking a smartphone, accessing a bank account, chatting with acquaintances, email composition, posting content on a social network, and e-learning [4]. As a means of subject authentication, keystroke dynamics is economical because it can be deployed on commodity hardware and remains transparent to the user. These properties have prompted several companies to capture and analyze keystrokes. The global keystroke biometrics market is projected to grow from \$129.8 million dollars (2017 estimate) to \$754.9 million by 2025, a rate of up to 25% per year¹. As an example, Google has recently committed \$7

million dollars to fund TypingDNA², a startup company which authenticates people based on their typing behavior.

At the same time, the security challenges that keystroke biometrics promises to solve are constantly evolving and getting more sophisticated every year: identity fraud, account takeover, sending unauthorized emails, and credit card fraud are some examples³. These challenges are magnified when dealing with applications that have hundreds of thousands to millions of users. In this context, keystroke biometric algorithms capable of authenticating individuals while interacting with online applications are more necessary than ever. As an example of this, Wikipedia struggles to solve the problem of ‘edit wars’ that happens when different groups of editors represent opposing opinions. According to [5], up to 12% of the discussions in Wikipedia are devoted to revert changes and vandalism, suggesting that the Wikipedia criteria to identify and resolve controversial articles is highly contentious. Large scale keystroke biometrics algorithms could be used to detect these malicious editors among the thousands of editors who write articles in Wikipedia every day. Other applications of keystroke biometric technologies are found in e-learning platforms; student identity fraud and cheating are some challenges that virtual education technologies need to address to become a viable alternative to face-to-face education [4].

The literature on keystroke biometrics is extensive, but to the best of our knowledge, previous systems have only been evaluated with up to several hundred subjects and cannot deal with the recent challenges that massive usage applications are facing. The aim of this paper is to explore the feasibility and limits of deep learning architectures for scaling up free-text keystroke biometrics to hundreds of thousands of users. The main contributions of this work are threefold:

- 1) We introduce TypeNet, a free-text keystroke biometrics system based on a Recurrent Neural Network (RNN) trained with thousands of subjects, suitable for authentication and identification at large scale. We conduct an exhaustive experimentation and evaluate performance as a function of keystroke sequence length, number of gallery samples, and device (touchscreen vs physical keyboard). We additionally compare the performance of three different loss functions (softmax, contrastive, triplet) used to train TypeNet. The results reported by TypeNet represent the state of the art in keystroke authentication based on free-text. Processed data has been made available so the results can be reproduced⁴.
- 2) We evaluate TypeNet in terms of Equal Error Rate (EER) as the number of test subjects is scaled from 100 up

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¹<https://www.prnewswire.com/news-releases/keystroke>

²<https://siliconcanals.com/news/>

³<https://150sec.com/fraudulent-fingertips>

⁴Data available at: <https://github.com/BiDALab/TypeNet>

to 100,000 (independent from the training data) for the desktop scenario (physical keyboards) and up to 30,000 for the mobile scenario (touchscreen keyboard). TypeNet learns a feature representation of a keystroke sequence without the need for retraining if new subjects are added to the database, as commonly happens in many biometric systems [6]. Therefore, TypeNet is easily scalable.

- 3) We carry out a comparison with previous state-of-the-art approaches for free-text keystroke biometric authentication. The performance achieved by the proposed method outperforms previous approaches in the scenarios evaluated in this work. The results suggest that authentication error rates achieved by TypeNet remain low as thousands of new users are enrolled.

A preliminary version of this article was presented in [7]. This article significantly improves [7] in the following aspects:

- 1) We add a new version of TypeNet trained and tested with keystroke sequences acquired in mobile devices and results in the mobile scenario. Additionally, we provide cross-sensor interoperability results [8] between desktop and mobile datasets.
- 2) We include two new loss functions (softmax and triplet loss) that serve to improve the performances in all scenarios.
- 3) We evaluate TypeNet in terms of Rank-n identification rates using a background set of 1,000 subjects (independent from the training data).
- 4) We add experiments about the dependencies between input text and TypeNet performance, a common issue in free-text keystroke biometrics.

In summary, we present the first evidence in the literature of competitive performance of free-text keystroke biometric authentication at large scale (up to 100,000 test subjects). The results reported in this work demonstrate the potential of this behavioral biometric for widespread deployment.

The paper is organized as follows: Section II summarizes related works in free-text keystroke dynamics. Section III describes the datasets used for training and testing TypeNet models. Section IV describes the processing steps and learning methods in TypeNet. Section V details the experimental protocol. Section VI reports the experiments and discusses the results obtained. Section VII summarizes the conclusions and future work.

II. BACKGROUND AND RELATED WORK

The measurement of keystroke dynamics depends on the acquisition of key press and release events. This can occur on almost any commodity device that supports text entry, including desktop and laptop computers, mobile and touchscreen devices that implement soft (virtual) keyboards, and PIN entry devices such as those used to process credit card transactions. Generally, each keystroke (the action of pressing and releasing a single key) results in a keydown event followed by keyup event, and the sequence of these timings is used to characterize an individual's keystroke dynamics. Within a web browser, the acquisition of keydown and keyup event timings requires

no special permissions, enabling the deployment of keystroke biometric systems across the Internet in a transparent manner.

Keystroke biometric systems are commonly placed into two categories: *fixed-text*, where the keystroke sequence typed by the subject is prefixed, such as a username or password, and *free-text*, where the keystroke sequence is arbitrary, such as writing an email or transcribing a sentence with typing errors. Notably, free-text input results in different keystroke sequences between the gallery and test samples as opposed to fixed-text input. Biometric authentication algorithms based on keystroke dynamics for desktop and laptop keyboards have been predominantly studied in fixed-text scenarios where accuracies higher than 95% are common [17]. Approaches based on sample alignment (e.g. Dynamic Time Warping) [17], Manhattan distances [18], digraphs [19], and statistical models (e.g. Hidden Markov Models) [20] have shown to achieve the best results in fixed-text.

Nevertheless, the performances of free-text algorithms are generally far from those reached in the fixed-text scenario, where the complexity and variability of the text entry contribute to intra-subject variations in behavior, challenging the ability to recognize subjects [21]. Monroe and Rubin [9] proposed in 1997 a free-text keystroke algorithm based on subject profiling by using the mean latency and standard deviation of digraphs and computing the Euclidean distance between each test sample and the reference profile. Their results worsened from 90% to 23% of correct classification rates when they changed both subject profiles and test samples from fixed-text to free-text. Gunetti and Picardi [10] extended the previous algorithm to n-graphs. They calculated the duration of n-graphs common between training and testing and defined a distance function based on the duration and order of such n-graphs. Their results of 7.33% classification error outperformed the previous state of the art. Nevertheless, their algorithm needs long keystroke sequences (between 700 and 900 keystrokes) and many keystroke sequences (up to 14) to build the subject profile, which limits the usability of that approach. Murphy *et al.* [14] more recently collected a very large free-text keystroke dataset (~ 2.9 M keystrokes) and applied the Gunetti and Picardi algorithm achieving 10.36% classification error using sequences of 1,000 keystrokes and 10 genuine sequences to authenticate subjects.

More recently than the pioneering works of Monroe and Gunetti, some algorithms based on statistical models have shown to work very well with free-text, like the POHMM (Partially Observable Hidden Markov Model) [15]. This algorithm is an extension of the traditional Hidden Markov Model (HMM), but with the difference that each hidden state is conditioned on an independent Markov chain. This algorithm is motivated by the idea that keystroke timings depend both on past events and the particular key that was pressed. Performance achieved using this approach in free-text is close to fixed-text, but it again requires several hundred keystrokes and has only been evaluated with a database containing less than 100 subjects.

The performance of keystroke biometric systems on mobile devices can in some cases exceed that of desktop systems. Unlike physical keyboards, touchscreen keyboards support a

Study	Scenario	#Subjects	#Seq.	Sequence Size	#Keys	Best Performance
Monrose and Rubin (1997) [9]	Desktop	31	N/A	N/A	N/A	ACC = 23%
Gunetti and Picardi (2005) [10]	Desktop	205	1 ~ 15	700 ~ 900 keys	688K	EER = 7.33%
Kim and Kang (2009) [11]	Mobile	50	20	~200 keys	200K	EER= 0.05%
Gascon <i>et al.</i> (2014) [12]	Mobile	315	1 ~ 10	~160 keys	67K	EER= 10.0%
Ceker and Upadhyaya (2016) [13]	Desktop	34	2	~7K keys	442K	EER = 2.94%
Murphy <i>et al.</i> (2017) [14]	Desktop	103	N/A	1,000 keys	12.9M	EER = 10.36%
Monaco and Tappert (2018) [15]	Both	55	6	500 keys	165K	EER = 0.6%
Deb <i>et al.</i> (2019) [16]	Mobile	37	180K	3 seconds	6.7M	81.61% TAR at 0.1% FAR
Ours (2020)	Both	228K	15	~70 keys	199M	EER= 2.2%

TABLE I

COMPARISON AMONG DIFFERENT FREE-TEXT KEYSTROKE DATASETS EMPLOYED IN RELEVANT RELATED WORKS. N/A = NOT AVAILABLE. ACC = ACCURACY, EER = EQUAL ERROR RATE, TAR = TRUE ACCEPTANCE RATE, FAR = FALSE ACCEPTANCE RATE.

variety of input methods, such as *swipe* which enables text entry by sliding the finger along a path that visits each letter and lifting the finger only between words. The ability to enter text in ways other than physical key pressing has led to a greater variety of text entry strategies employed by typists [22]. In addition to this, mobile devices are readily equipped with additional sensors which offer more insight to a users keystroke dynamics. This includes the touchscreen itself, which is able to sense the location and pressure, as well as accelerometer, gyroscope, and orientation sensors.

Like desktop keystroke biometrics, many mobile keystroke biometric studies have focused on fixed-text sequences [23]. Some recent works have considered free-text sequences on mobile devices. Gascon *et al.* [12] collected freely typed samples from over 300 participants and developed a system that achieved a True Acceptance Rate (TAR) of 92% at 1% False Acceptance Rate (FAR) (an EER of about 10%). Their system utilized accelerometer, gyroscope, time, and orientation features. Each user typed an English pangram (sentence containing every letter of the alphabet) approximately 160 characters in length, and classification was performed by Support Vector Machine (SVM). In other work, Kim and Kang [11] utilized microbehavioral features to obtain an EER below 0.05% for 50 subjects with a single reference sample of approximately 200 keystrokes for both English and Korean input. The microbehavioral features consist of angular velocities along three axes when each key is pressed and released, as well as timing features and the coordinate of the touch event within each key. See [23] for a survey of keystroke biometrics on mobile devices.

Because mobile devices are not stationary, mobile keystroke biometrics depend more heavily on environmental conditions, such as the user's location or posture, than physical keyboards which typically remain stationary. This challenge of mobile keystroke biometrics was examined by Crawford and Ahmadzadeh in [24]. They found that authenticating a user in different positions (sitting, standing, or walking) performed only slightly better than guessing, but detecting the user's position before authentication can significantly improve performance.

Nowadays, with the proliferation of machine learning algorithms capable of analysing and learning human behaviors from large scale datasets, the performance of keystroke dynamics in the free-text scenario has been boosted. As an example, [13] proposes a combination of the existing digraphs method for feature extraction plus an SVM classifier to authenticate

subjects. This approach achieves almost 0% error rate using samples containing 500 keystrokes. These results are very promising, even though it was evaluated using a small dataset with only 34 subjects. In [16] the authors employ an RNN within a Siamese architecture to authenticate subjects based on 8 biometric modalities on smartphone devices. They achieved results in a free-text scenario of 81.61% TAR at 0.1% FAR using just 3 second test windows with a dataset of 37 subjects.

Previous works in free-text keystroke dynamics have achieved promising results with up to several hundred subjects (see Table I), but they have yet to scale beyond this limit and leverage emerging machine learning techniques that benefit from vast amounts of data. Here we take a step forward in this direction of machine learning-based free-text keystroke biometrics by using the largest datasets published to date with 199 million keystrokes from 228,000 subjects (considering both mobile and desktop datasets). We analyze to what extent deep learning models are able to scale in keystroke biometrics to recognize subjects at a large scale while attempting to minimize the amount of data per subject required for enrollment.

III. KEYSTROKE DATASETS

All experiments are conducted with two Aalto University Datasets: 1) the Dhakal *et al.* dataset [25], which comprises more than 5GB of keystroke data collected on desktop keyboards from 168,000 participants; and 2) the Palin *et al.* dataset [22], which comprises almost 4GB of keystroke data collected on mobile devices from 260,000 participants. The same data collection procedure was followed for both datasets. The acquisition task required subjects to memorize English sentences and then type them as quickly and accurate as they could. The English sentences were selected randomly from a set of 1,525 examples taken from the Enron mobile email and Gigaword Newswire corpus. The example sentences contained a minimum of 3 words and a maximum of 70 characters. Note that the sentences typed by the participants could contain more than 70 characters because each participant could forget or add new characters when typing. All participants in the Dhakal database completed 15 sessions (i.e. one sentence for each session) on either a desktop or a laptop physical keyboard. However, in the Palin dataset the participants who finished at least 15 sessions are only 23% (60,000 participants) out of 260,000 participants that started the typing test. In this paper we will employ these 60,000 subjects with their first

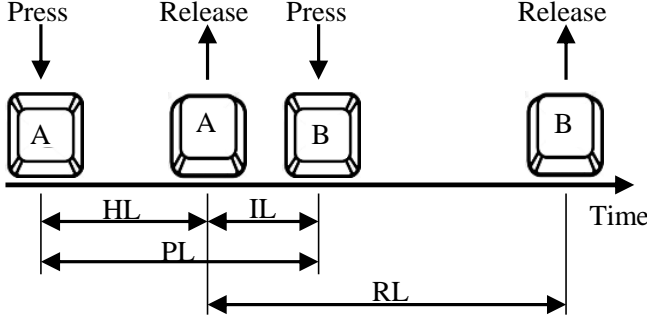


Fig. 1. Example of the 4 temporal features extracted between two consecutive keys: Hold Latency (HL), Inter-key Latency (IL), Press Latency (PL), and Release Latency (RL).

15 sessions in order to allow fair comparisons between both datasets.

For the data acquisition, the authors launched an online application that records the keystroke data from participants who visit their webpage and agree to complete the acquisition task (i.e. the data was collected in an uncontrolled environment). Press (keydown) and release (keyup) event timings were recorded in the browser with millisecond resolution using the JavaScript function `Date.now`. The authors also reported demographic statistics for both datasets: 72% of the participants from the Dhakal database took a typing course, 218 countries were involved, and 85% of the them have English as native language, meanwhile only 31% of the participants from the Palin database took a typing course, 163 countries were involved, and 68% of the them were English native speakers.

IV. SYSTEM DESCRIPTION

A. Pre-processing and Feature Extraction

The raw data captured in each session includes a time series with three dimensions: the keycodes, press times, and release times of the keystroke sequence. Timestamps are in UTC format with millisecond resolution, and the keycodes are integers between 0 and 255 according to the ASCII code.

We extract 4 temporal features for each sequence (see Fig. 1 for details): (i) Hold Latency (HL), the elapsed time between key press and release events; (ii) Inter-key Latency (IL), the elapsed time between releasing a key and pressing the next key; (iii) Press Latency (PL), the elapsed time between two consecutive press events; and (iv) Release Latency (RL), the elapsed time between two consecutive release events. These 4 features are commonly used in both fixed-text and free-text keystroke systems [26]. Finally, we include the keycodes as an additional feature.

The 5 features are calculated for each keystroke in the sequence. Let N be the length of the keystroke sequence, such that each sequence provided as input to the model is a time series with shape $N \times 5$ (N keystrokes by 5 features). All feature values are normalized before being provided as input to the model. Normalization is important so that the activation values of neurons in the input layer of the network do not saturate (i.e. all close to 1). The keycodes are normalized to between 0 and 1 by dividing each keycode by 255, and the

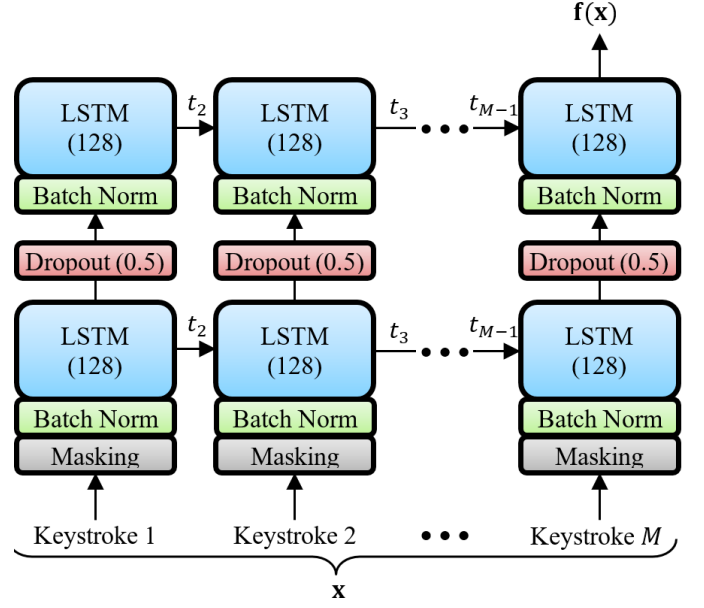


Fig. 2. Architecture of TypeNet for free-text keystroke sequences. The input \mathbf{x} is a time series with shape $M \times 5$ (keystrokes \times keystroke features) and the output $\mathbf{f}(\mathbf{x})$ is an embedding vector with shape 1×128 .

4 timing features are converted to seconds. This scales most timing features to between 0 and 1 as the average typing rate over the entire dataset is 5.1 ± 2.1 keys per second. Only latency features that occur either during very slow typing or long pauses exceed a value of 1.

B. TypeNet Architecture

In keystroke dynamics, it is thought that idiosyncratic behaviors that enable authentication are characterized by the relationship between consecutive key press and release events (e.g. temporal patterns, typing rhythms, pauses, typing errors). In a free-text scenario, keystroke sequences between enrollment and testing may differ in both length and content. This reason motivates us to choose a Recurrent Neural Network as our keystroke authentication algorithm. RNNs have demonstrated to be one of the best algorithms to deal with temporal data (e.g. [27], [28]) and are well suited for free-text keystroke sequences (e.g. [16], [29]).

Our RNN architecture is depicted in Fig. 2. It is composed of two Long Short-Term Memory (LSTM) layers of 128 units (*tanh* activation function). Between the LSTM layers, we perform batch normalization and dropout at a rate of 0.5 to avoid overfitting. Additionally, each LSTM layer has a recurrent dropout rate of 0.2.

One constraint when training a RNN using standard back-propagation through time applied to a batch of sequences is that the number of elements in the time dimension (i.e. number of keystrokes) must be the same for all sequences. We set the size of the time dimension to M . In order to train the model with sequences of different lengths N within a single batch, we truncate the end of the input sequence when $N > M$ and zero pad at the end when $N < M$, in both cases to the fixed size M . Error gradients are not computed for those zeros and

do not contribute to the loss function at the output layer as a result of the masking layer shown in Fig. 2.

Finally, the output of the model $\mathbf{f}(\mathbf{x})$ is an array of size 1×128 that we will employ later as an embedding feature vector to recognize subjects.

C. LSTM Training: Loss Functions

Our goal is to build a keystroke biometric system capable of generalizing to new subjects not seen during model training, and therefore, having a competitive performance when it deploys to applications with thousands of users. Our RNN is trained only once on an independent set of subjects. This model then acts as a feature extractor that provides input to a distance-based recognition scheme. After training the RNN once, we will evaluate in the experimental section the recognition performance for a varying number of subjects and enrollment samples per subject.

We train our deep model with three different loss functions: *Softmax loss*, which is widely used in classification tasks; *Contrastive loss*, a loss for distance metric learning based on two samples [30]; and *Triplet loss*, a loss for metric learning based on three samples [31]. These are each defined as follows.

1) *Softmax loss*: Let \mathbf{x}_i be a keystroke sequence of individual I_i , and let us introduce a dense layer after the embeddings described in the previous section aimed at classifying the individuals used for learning (see Fig. 3.a). The Softmax loss is applied as

$$\mathcal{L}_S = -\log \left(\frac{e^{f_{I_i}^C(\mathbf{x}_i)}}{\sum_{c=1}^C e^{f_c^C(\mathbf{x}_i)}} \right) \quad (1)$$

where C is the number of classes used for learning (i.e. identities), $\mathbf{f}^C = [f_1^C, \dots, f_C^C]$, and after learning all elements of \mathbf{f}^C will tend to 0 except $f_{I_i}^C(\mathbf{x}_i)$ that will tend to 1. Softmax is widely used in classification tasks because it provides good performance on closed-set problems. Nonetheless, Softmax does not optimize the margin between classes. Thus, the performance of this loss function usually decays for problems with high intra-class variance. In order to train the architecture proposed in Fig. 2, we have added an output classification layer with C units (see Fig. 3.a). During the training phase, the model will learn discriminative information from the keystroke sequences and transform this information into an embedding space where the embedding vectors $\mathbf{f}(\mathbf{x})$ (the outputs of the model) will be close in case both keystroke inputs belong to the same subject (genuine pairs), and far in the opposite case (impostor pairs).

2) *Contrastive loss*: Let \mathbf{x}_i and \mathbf{x}_j each be a keystroke sequence that together form a pair which is provided as input to the model. The Contrastive loss calculates the Euclidean distance between the model outputs,

$$d(\mathbf{x}_i, \mathbf{x}_j) = \|\mathbf{f}(\mathbf{x}_i) - \mathbf{f}(\mathbf{x}_j)\| \quad (2)$$

where $\mathbf{f}(\mathbf{x}_i)$ and $\mathbf{f}(\mathbf{x}_j)$ are the model outputs (embedding vectors) for the inputs \mathbf{x}_i and \mathbf{x}_j , respectively. The model will

learn to make this distance small (close to 0) when the input pair is genuine and large (close to α) for impostor pairs by computing the loss function \mathcal{L}_{CL} defined as follows:

$$\mathcal{L}_{CL} = (1 - L_{ij}) \frac{d^2(\mathbf{x}_i, \mathbf{x}_j)}{2} + L_{ij} \frac{\max^2\{0, \alpha - d(\mathbf{x}_i, \mathbf{x}_j)\}}{2} \quad (3)$$

where L_{ij} is the label associated with each pair that is set to 0 for genuine pairs and 1 for impostor ones, and $\alpha \geq 0$ is the margin (the maximum margin between genuine and impostor distances). The Contrastive loss is trained using a Siamese architecture (see Fig. 3.b) that minimizes the distance between embeddings vectors from the same class ($d(\mathbf{x}_i, \mathbf{x}_j)$ with $L_{ij} = 0$), and maximizes it for embeddings from different class ($d(\mathbf{x}_i, \mathbf{x}_j)$ with $L_{ij} = 1$).

3) *Triplet loss*: The *Triplet loss* function enables learning from positive and negative comparisons at the same time (note that the label L_{ij} eliminates one of the distances for each pair in the Contrastive loss). A triplet is composed by three different samples from two different classes: Anchor (A) and Positive (P) are different keystroke sequences from the same subject, and Negative (N) is a keystroke sequence from a different subject. The Triplet loss function is defined as follows:

$$\mathcal{L}_{TL} = \max \left\{ 0, d^2(\mathbf{x}_A^i, \mathbf{x}_P^i) - d^2(\mathbf{x}_A^i, \mathbf{x}_N^j) + \alpha \right\} \quad (4)$$

where α is a margin between positive and negative pairs and d is the Euclidean distance calculated with Eq. 2. In comparison with Contrastive loss, Triplet loss is capable of learning intra- and inter-class structures in a unique operation (removing the label L_{ij}). The Triplet loss is trained using an extension of a Siamese architecture (see Fig. 3.c) for three samples. This learning process minimizes the distance between embedding vectors from the same class ($d(\mathbf{x}_A, \mathbf{x}_P)$), and maximizes it for embeddings from different classes ($d(\mathbf{x}_A, \mathbf{x}_N)$).

D. LSTM Training: Implementation Details

We train three RNN versions (i.e. one for each loss function) for each input device: desktop and mobile, using the Dhakal and Palin databases, respectively. For the desktop scenario, we train the models using only the first 68,000 subjects from the Dhakal dataset. For the Softmax function we train a model with $C = 10,000$ subjects due to GPU memory constraints, as the Softmax loss requires a very wide final layer with many classes. In this case, we used $15 \times 10,000 = 150,000$ keystroke sequences for training and the remaining 58,000 subjects were discarded. For the Contrastive loss we generate genuine and impostor pairs using all the 15 keystroke sequences available for each subject. This provides us with $15 \times 67,999 \times 15 = 15.3$ million impostor pair combinations and $15 \times 14/2 = 105$ genuine pair combinations for each subject. The pairs were chosen randomly in each training batch ensuring that the number of genuine and impostor pairs remains balanced (512 pairs in total in each batch including impostor and genuine pairs). Similarly, we randomly chose triplets for the Triplet loss training.

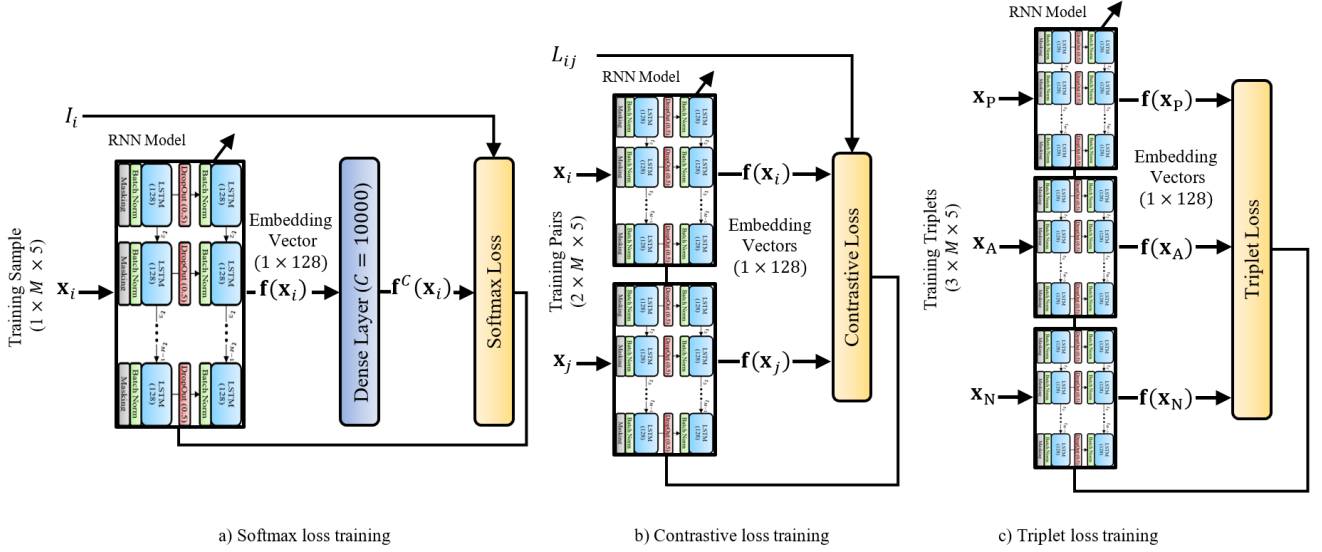


Fig. 3. Learning architecture for the different loss functions a) Softmax loss, b) Contrastive loss, and c) Triplet loss. The goal is to find the most discriminant embedding space $\mathbf{f}(\mathbf{x})$.

The remaining 100,000 subjects were employed only for model evaluation, so there is no data overlap between the two groups of subjects. This reflects an open-set authentication paradigm. The same protocol was employed for the mobile scenario but adjusting the amount of subjects employed to train and test. In order to have balanced subsets close to the desktop scenario, we divided by half the Palin database such that 30,000 subjects were used to train the models, generating $15 \times 29,999 \times 15 = 6.75$ million impostor pair combinations and $15 \times 14/2 = 105$ genuine pair combinations for each subject. The other 30,000 subjects were used to test the mobile TypeNet models. Once again 10,000 subjects were used to train the mobile TypeNet model with Softmax loss.

Regarding the hyper-parameters employed during training, the best results for both models were achieved with a learning rate of 0.05, Adam optimizer with $\beta_1 = 0.9$, $\beta_2 = 0.999$ and $\epsilon = 10^{-8}$, and the margin set to $\alpha = 1.5$. The models were trained for 200 epochs with 150 batches per epoch and 512 sequences in each batch. The models were built in Keras-Tensorflow.

V. EXPERIMENTAL PROTOCOL

A. Authentication Protocol

We authenticate subjects by comparing gallery samples $\mathbf{x}_{i,g}$ belonging to the subject i in the test set to a query sample $\mathbf{x}_{j,q}$ from either the same subject (genuine match $i = j$) or another subject (impostor match $i \neq j$). The test score is computed by averaging the Euclidean distances between each gallery embedding vector $\mathbf{f}(\mathbf{x}_{i,g})$ and the query embedding vector $\mathbf{f}(\mathbf{x}_{j,q})$ as follows:

$$s_{i,j}^q = \frac{1}{G} \sum_{g=1}^G \|\mathbf{f}(\mathbf{x}_{i,g}) - \mathbf{f}(\mathbf{x}_{j,q})\| \quad (5)$$

where G is the number of sequences in the gallery (i.e. the number of enrollment samples) and q is the query sample of

subject j . Taking into account that each subject has a total of 15 sequences, we retain 5 sequences per subject as the test set (i.e. each subject has 5 genuine test scores) and let G vary between $1 \leq G \leq 10$ in order to evaluate the performance as a function of the number of enrollment sequences.

To generate impostor scores, for each enrolled subject we choose one test sample from each remaining subject. We define k as the number of enrolled subjects. In our experiments, we vary k in the range $100 \leq k \leq K$, where $K = 100,000$ for the desktop TypeNet models and $K = 30,000$ for the mobile TypeNet. Therefore each subject has 5 genuine scores and $k-1$ impostor scores. Note that we have more impostor scores than genuine ones, a common scenario in keystroke dynamics authentication. The results reported in the next section are computed in terms of Equal Error Rate (EER), which is the value where False Acceptance Rate (FAR, proportion of impostors classified as genuine) and False Rejection Rate (FRR, proportion of genuine subjects classified as impostors) are equal. The error rates are calculated for each subject and then averaged over all k subjects [32].

B. Identification Protocol

Identification scenarios are common in forensics applications, where the final decision is based on a bag of evidences and the biometric recognition technology can be used to provide a list of candidates, referred to as background set \mathcal{B} in this work. The Rank-1 identification rate reveals the performance to unequivocally identifying the target subject among all the subjects in the background set. Rank- n represents the accuracy if we consider a ranked list of n profiles from which the result is then manually or automatically determined based on additional evidence [33].

The 15 sequences from the k test subjects in the database were divided into two groups: Gallery (10 sequences) and Query (5 sequences). We evaluate the identification rate by comparing the Query set of samples $\mathbf{x}_{j,q}^Q$, with $q = 1, \dots, 5$

belonging to the test subject j against the Background Gallery set $\mathbf{x}_{i,g}^G$, with $g = 1, \dots, 10$ belonging to all background subjects. The distance was computed by averaging the Euclidean distances $\|\cdot\|$ between each gallery embedding vector $\mathbf{f}(\mathbf{x}_{i,g}^G)$ and each query embedding vector $\mathbf{f}(\mathbf{x}_{j,q}^Q)$ as follows:

$$s_{i,j}^Q = \frac{1}{10 \times 5} \sum_{g=1}^{10} \sum_{q=1}^5 \|\mathbf{f}(\mathbf{x}_{i,g}^G) - \mathbf{f}(\mathbf{x}_{j,q}^Q)\| \quad (6)$$

We then identify a query set (i.e. subject $j = J$ is the same gallery person $i = I$) as follows:

$$I = \arg \min_i s_{i,J}^Q \quad (7)$$

The results reported in the next section are computed in terms of Rank- n accuracy. A Rank-1 means that $d_{i,J} < d_{I,J}$ for any $i \neq I$, while a Rank- n means that instead of selecting a single gallery profile, we select n profiles starting with $i = I$ by increasing distance $d_{i,J}$. In forensic scenarios, it is traditional to use Rank-20, Rank-50, or Rank-100 in order to generate a short list of potential candidates that are finally identified by considering other evidence.

VI. EXPERIMENTS AND RESULTS

A. Authentication: Varying Amount of Enrollment Data

As commented in the related works section, one key factor when analyzing the performance of a free-text keystroke authentication algorithm is the amount of keystroke data per subject employed for enrollment. In this work, we study this factor with two variables: the keystroke sequence length M and the number of gallery sequences used for enrollment G .

Our first experiment reveals to what extent M and G affect the authentication performance of our TypeNet models. Note that the input to our models has a fixed size of M after the masking process shown in Fig. 2. For this experiment, we set $k = 1,000$ (where k is the number of enrolled subjects). Tables II and III summarize the error rates in both desktop and mobile scenarios respectively, achieved by the TypeNet models for the different values of sequence length M and enrollment sequences per subject G .

In the desktop scenario (Table II) we observe that for sequences longer than $M = 70$ there is no significant improvement in performance. Adding three times more key events (from $M = 50$ to $M = 150$) lowers the EER by only 0.7% in average for all values of G . However, adding more sequences to the gallery shows greater improvements with about 50% relative error reduction when going from 1 to 10 sequences independent of M . Comparing among the different loss functions, the best results are always achieved by the model trained with Triplet loss for $M = 70$ and $G = 10$ with an error rate of 1.2%, followed by the Contrastive loss function with an error rate of 3.9%; the worst results are achieved with the Softmax loss function (6.0%). For one-shot authentication ($G = 1$), our approach has an error rate of 4.5% using sequences of 70 keystrokes.

Similar trends are observed in the mobile scenario (Table III) compared to the desktop scenario (Table II). First, increasing sequence length beyond $M = 70$ keystrokes does not

significantly improve performance, but there is a significant improvement when increasing the number of sequences per subject. The best results are achieved for $M = 100$ and $G = 10$ with an error rate of 6.3% by the model trained with triplet loss, followed again by the contrastive loss (10.0%), and softmax (12.3%). For one-shot authentication ($G = 1$), the performance of the triplet model decays up to 10.7% EER using sequences of $M = 100$ keystrokes.

Comparing the performance achieved by the three TypeNet models between mobile and desktop scenarios, we observe that in all cases the results achieved in the desktop scenario are significantly better to those achieved in the mobile scenario. These results are consistent with prior work that has obtained lower performance on mobile devices when only timing features are utilized [2], [23], [34].

Next, we compare TypeNet with our implementation of two state-of-the-art algorithms for free-text keystroke authentication: a statistical sequence model, the POHMM (Partially Observable Hidden Markov Model) from [15], and another algorithm based on digraphs and SVM from [13]. To allow fair comparisons, all approaches are trained and tested with the same data and experimental protocol: $G = 5$ enrollment sequences per subject, $M = 50$ keystrokes per sequence, $k = 1,000$ test subjects.

In Fig. 4 we plot the error rates of the three approaches (i.e. Digraphs, POHMM, and TypeNet) trained and tested on both desktop (left) and mobile (right) datasets. The TypeNet models outperform previous state-of-the-art free-text algorithms in both mobile and desktop scenarios with this experimental protocol, where the amount of enrollment data is reduced ($5 \times M = 250$ training keystrokes in comparison to more than 10,000 in related works, see Section II). This can largely be attributed to the rich embedding feature vector produced by TypeNet, which minimizes the amount of data needed for enrollment. The SVM generally requires a large number of training sequences per subject (~ 100), whereas in this experiment we have only 5 training sequences per subject. We hypothesize that the lack of training samples contributes to the poor performance (near chance accuracy) of the Digraphs system based on SVMs.

B. Authentication: Varying Number of Subjects

In this experiment, we evaluate to what extent our best TypeNet models (those trained with triplet loss) are able to generalize without performance decay. For this, we scale the number of enrolled subjects k from 100 to K (with $K = 100,000$ for desktop and $K = 30,000$ for mobile). For each subject we have 5 genuine test scores and $k - 1$ impostor scores, one against each other test subject. The models used for this experiment are the same trained in previous the section (68,000 independent subjects included in the training phase for desktop and 30,000 for mobile).

Fig. 5 shows the authentication results for one-shot enrollment ($G = 1$ enrollment sequences, $M = 50$ keystrokes per sequence) and the case ($G = 5$, $M = 50$) for different values of k . For the desktop devices, we can observe that in both cases there is a slight performance decay when we

		#enrollment sequences per subject G				
		1	2	5	7	10
#keys per sequence M	30	17.2/10.7/8.6	14.1/9.0/6.4	13.3/7.3/4.6	12.7/6.8/4.1	11.5/3.3/3.7
	50	16.8/8.2/5.4	13.1/6.7/3.6	10.8/5.4/2.2	9.2/4.8/1.8	8.8/4.3/1.6
	70	14.1/7.7/4.5	10.4/6.2/2.8	7.5/4.8/1.7	6.7/4.3/1.4	6.0/3.9/1.2
	100	13.8/7.7/4.2	10.1/6.0/2.7	7.4/4.7/1.6	6.4/4.3/1.4	5.7/3.9/1.2
	150	13.8/7.7/4.1	10.1/6.0/2.7	7.4/4.7/1.6	6.5/4.3/1.4	5.8/3.8/1.2

TABLE II

EQUAL ERROR RATES (%) ACHIEVED IN **DESKTOP** SCENARIO USING SOFTMAX/CONTRASTIVE/TRIPLET LOSS FOR DIFFERENT VALUES OF THE PARAMETERS M (SEQUENCE LENGTH) AND G (NUMBER OF ENROLLMENT SEQUENCES PER SUBJECT).

		#enrollment sequences per subject G				
		1	2	5	7	10
#keys per sequence M	30	17.7/15.7/14.2	16.0/14.1/12.5	15.2/13.0/11.3	14.9/12.6/10.9	14.5/12.1/10.5
	50	17.2/14.6/12.6	15.4/13.1/10.7	13.8/12.1/9.2	13.4/11.5/8.5	12.7/11.0/8.0
	70	17.8/13.8/11.3	15.5/12.4/9.5	13.5/11.2/7.8	13.0/10.7/7.2	12.1/10.4/6.8
	100	18.4/13.6/10.7	15.8/12.3/8.9	13.6/10.9/7.3	13.0/10.4/6.6	12.3/10.0/6.3
	150	18.4/13.7/10.7	15.9/12.3/8.8	13.7/10.8/7.3	13.0/10.4/6.6	12.3/10.0/6.3

TABLE III

EQUAL ERROR RATES (%) ACHIEVED IN **MOBILE** SCENARIO USING SOFTMAX/CONTRASTIVE/TRIPLET LOSS FOR DIFFERENT VALUES OF THE PARAMETERS M (SEQUENCE LENGTH) AND G (NUMBER OF ENROLLMENT SEQUENCES PER SUBJECT).

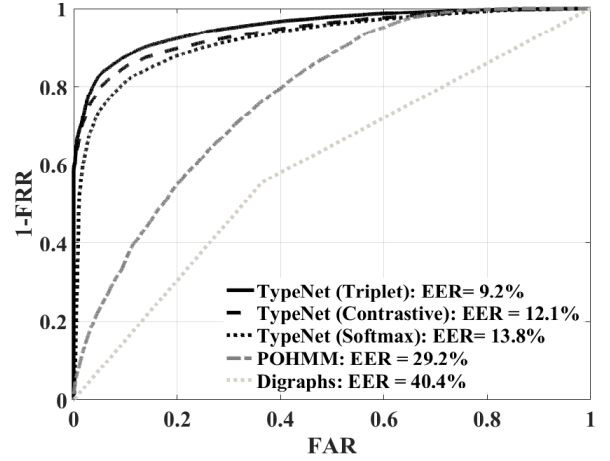
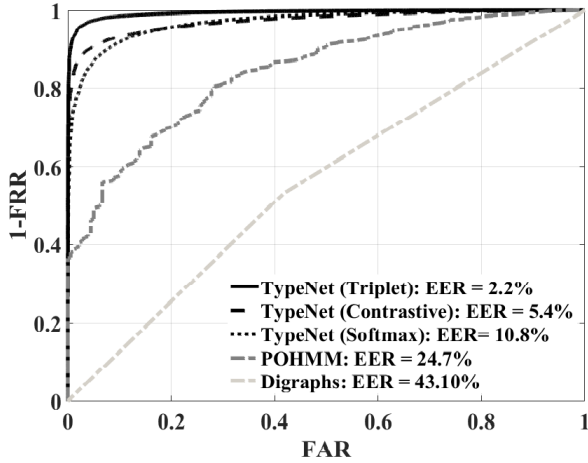


Fig. 4. ROC comparisons in free-text biometric authentication for desktop (left) and mobile (right) scenarios between the three proposed TypeNet models and two state-of-the-art approaches: POHMM from [15] and digraphs/SVM from [13]. $M = 50$ keystrokes per sequence, $G = 5$ enrollment sequences per subject, and $k = 1,000$ test subjects.

scale from 1,000 to 10,000 test subjects, which is more pronounced in the one-shot case. However, for a large number of subjects ($k \geq 10,000$), the error rates do not appear to demonstrate continued growth. For the mobile scenario, the results when scaling from 100 to 1,000 test subjects show a similar tendency compared to the desktop scenario with a slightly greater performance decay. However, we can observe an error rate reduction when we continue scaling the number

of test subjects up to 30,000. In all cases the variation of the performance across the number of test subjects is less than 2.5% EER. These results demonstrate the potential of the RNN architecture in TypeNet to authenticate subjects at large scale in free-text keystroke dynamics. We note that in the mobile scenario, we have utilized only timing features; prior work has found that greater performance may be achieved by incorporating additional sensor features [11].

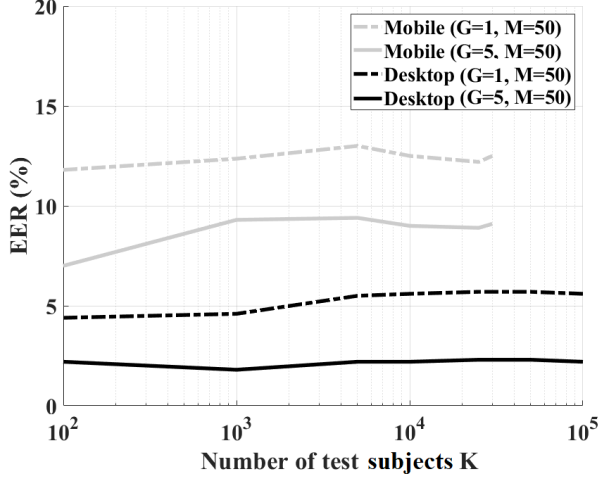


Fig. 5. EER (%) of our proposed TypeNet models when scaling up the number of test subjects k in one-shot ($G = 1$ enrollment sequences per subject) and 5-shot ($G = 5$) authentication cases. $M = 50$ keystrokes per sequence.

		TypeNet model		
		Desktop	Mobile	Mixture
Test dataset	Desktop	2.2	21.4	17.9
	Mobile	13.7	9.2	12.6

TABLE IV
EQUAL ERROR RATES (%) ACHIEVED IN THE CROSS-DEVICE SCENARIO FOR THE THREE TYPENET MODELS (DESKTOP, MOBILE, AND MIXTURE) WHEN TESTING ON EITHER DESKTOP [25] OR MOBILE [22] DATASET.

C. Authentication: Cross-device Interoperability

In this experiment we measure the cross-device interoperability between the best TypeNet models trained with the triplet loss. We also study the capacity of both desktop and mobile TypeNet models to generalize to other input devices. For this, we test both models with a different keystroke dataset than the one employed in their training. Additionally, for this experiment we train a third TypeNet model called Mixture-TypeNet with triplet loss using keystroke sequences from both datasets (half of the training batch for each dataset) but keeping the same train/test subject division as the other TypeNet models to allow fair comparisons. To be consistent with the other experiments we keep the same experimental protocol: $G = 5$ enrollment sequences per subject, $M = 50$ keystrokes per sequence, $k = 1,000$ test subjects.

Table IV shows the error rates achieved for the three TypeNet models when we test with desktop (Dhakal) and mobile (Palin) datasets. We can observe that error rates increase significantly in the cross-device scenario for both desktop and mobile TypeNet models. This performance decay is alleviated by the Mixture-TypeNet model, which still performs much worse than the other two models trained and tested in the same-sensor scenario. These results suggest that multiple device-specific models may be superior to a single model when

Method	Scenario	Rank		
		1	50	100
Digraph [13]	D	0.1	9.5	15.2
Digraph [13]	M	0.0	8.5	14.4
POHMM [15]	D	6.1	48.4	63.4
POHMM [15]	M	6.5	41.8	53.7
TypeNet (softmax)	D	47.5	96.3	98.7
TypeNet (softmax)	M	23.5	82.6	91.4
TypeNet (contrastive)	D	29.4	97.2	99.3
TypeNet (contrastive)	M	19.0	80.4	89.8
TypeNet (triplet)	D	67.4	99.8	99.9
TypeNet (triplet)	M	25.5	87.5	94.2

TABLE V
IDENTIFICATION ACCURACY (RANK- n IN %) FOR A BACKGROUND SIZE $\mathfrak{B} = 1,000$. SCENARIO: D = DESKTOP, M = MOBILE.

dealing with input from different device types. This would require device type detection in order to pass the enrollment and test samples to the correct model [8].

D. Identification based on Keystroke Dynamics

Table V presents the identification accuracy for a background of $\mathfrak{B} = 1,000$ subjects, $k = 10,000$ test subjects, $G = 10$ gallery sequences per subject, and $M = 50$ keystrokes per sequence. The accuracy obtained for an identification scenario is much lower than the accuracy reported for authentication. In general, the results suggest that keystroke identification enables a 90% size reduction of the candidate list while maintaining almost 100% accuracy (i.e., 100% rank-100 accuracy with 1,000 subjects). However, the results show the superior performance of the triplet loss function and significantly better performance compared to traditional keystroke approaches [13], [15]. While traditional approaches are not suitable for large-scale free text keystroke applications, the results obtained by TypeNet demonstrate its usefulness in many applications.

The number of background profiles can be further reduced if auxiliary data is available to realize a pre-screening of the initial list of gallery profiles (e.g. country, language). The Aalto University Dataset contains auxiliary data including age, country, gender, keyboard type (desktop vs laptop), among others. Table VI shows also subject identification accuracy over the 1,000 subjects with a pre-screening by country (i.e., contents generated in a country different to the country of the target subject are removed from the background set). The results show that pre-screening based on a unique attribute is enough to largely improve the identification rate: Rank-1 identification with pre-screening ranges between 5.5% to 84.0%, while the Rank-100 ranges between 42.2% to 100%. These results demonstrate the potential of keystroke dynamics for large-scale identification when auxiliary information is available.

Method	Scenario	Rank		
		1	50	100
Digraph [13]	D	5.5	37.6	42.2
POHMM [15]	D	21.8	78.3	89.7
TypeNet (softmax)	D	68.3	99.39	99.9
TypeNet (contrastive)	D	56.3	99.7	99.9
TypeNet (triplet)	D	84.0	99.9	100

TABLE VI

IDENTIFICATION ACCURACY (RANK- n IN %) FOR A BACKGROUND SIZE $\mathfrak{B} = 1,000$ AND PRE-SCREENING BASED ON THE LOCATION OF THE TYPIST. SCENARIO: D = DESKTOP. THERE IS NOT METADATA RELATED TO THE MOBILE SCENARIO.

E. Input Text Dependency in TypeNet Models

For the last experiment, we examine the effect of the text typed (i.e. the keycodes employed as input feature in the TypeNet models) on the distances between embedding vectors and how this may affect the model performance. The main drawback when using the keycode as an input feature to free-text keystroke algorithms is that the model could potentially learn text-based features (e.g. orthography, linguistic expressions, typing styles) rather than keystroke dynamics (e.g., typing speed and style) features. To analyze this phenomenon, we first introduce the Levenshtein distance (commonly referred as *Edit distance*) proposed in [35]. The Levenshtein distance d_L measures the distance between two words as the minimum number of single-character edits (insertions, deletions or substitutions) required to change one word into another. As an example, the Levenshtein distance between “kitten” and “sitting” is $d_L = 3$, because we need to substitute “s” for “k”, substitute “i” for “e”, and insert “g” at the end (three editions in total). With the Levenshtein distance metric we can measure the similarity of two keystroke sequences in terms of keys pressed and analyze whether TypeNet models could be learning linguistic expressions to recognize subjects. This would be revealed by a high correlation between Levenshtein distance d_L and the Euclidean distance of test scores d_E .

In Fig. 6 we plot the test scores (Euclidean distances) employed in one-shot scenario ($G = 1$ enrollment sequence per subject, $M = 50$ keystrokes per sequence, $k = 1,000$ test subjects) versus the Levenshtein distance between the gallery and the query sample that produced the test score (i.e. $d_E(\mathbf{f}(\mathbf{x}_g), \mathbf{f}(\mathbf{x}_q))$ vs. $d_L(\mathbf{x}_g, \mathbf{x}_q)$). To provide a quantitative comparison, we also calculate the Pearson coefficient p and the Linear Regression response as a measure of correlation between both distances (smaller slope indicates a weaker relationship). In mobile scenarios (Fig. 6 down) we can observe a significant correlation (i.e higher slope in the Linear Regression response and high p value) between the Levenshtein distances and the test scores: genuine distance scores show lower Levenshtein distances (i.e. more similar typed text) than the impostor ones, and therefore, this metric provides us some clues about the possibility that TypeNet models in the mobile scenario could be using the similarity of linguistic expressions or keys pressed between the gallery and

the query samples to recognize subjects. These results suggest us that the TypeNet models trained in the mobile scenario may be performing worse than in the desktop scenario, among other factors, because mobile TypeNet embeddings show a significant dependency to the entry text. On the other hand, in desktop scenarios (Fig. 6 up) this correlation is not present (i.e. the small slope in the Linear Regression response and $p \sim 0$) between test scores and Levenshtein distances, suggesting that the embedding vector produced by TypeNet models trained with the desktop dataset are largely independent of the input text.

VII. CONCLUSIONS AND FUTURE WORK

We have presented TypeNet, a new free-text keystroke biometrics system based on an RNN architecture trained with three different loss functions: softmax, contrastive, and triplet. Authentication and identificatino results were obtain with two datasets at very large scale: one dataset composed of 136 million keystrokes from 168,000 subjects captured on desktop keyboards and a second composed of 60,000 subjects captured on mobile devices with more than 63 million keystrokes. Deep neural networks have shown to be effective in face recognition tasks when scaling up to hundreds of thousands of identities [36]. The same capacity has been shown by TypeNet models in free-text keystroke biometrics.

In all authentication scenarios evaluated in this work, the models trained with triplet loss have shown a superior performance, especially when there are many subjects but few enrollment samples per subject. The results achieved in this work outperform previous state-of-the-art algorithms. Our results range from 17.2% to 1.2% EER in desktop and from 17.7% to 6.3% EER in mobile scenarios depending on the amount of subject data enrolled. A good balance between performance and the amount of enrollment data per subject is achieved with 5 enrollment sequences and 50 keystrokes per sequence, which yields an EER of 2.2/9.2% (desktop/mobile) for 1,000 test subjects. These results suggest that our approach achieves error rates close to those achieved by the state-of-the-art fixed-text algorithms [17], within $\sim 5\%$ of error rate even when the enrollment data is scarce.

Scaling up the number of test subjects does not significantly affect the performance: the EER in the desktop scenario increases only 5% in relative terms with respect to the previous 2.2% when scaling up from 1,000 to 100,000 test subjects, while in the mobile scenario decays up to 15% the EER in relative terms. Evidence of the EER stabilizing around 10,000 subjects demonstrates the potential of this architecture to perform well at large scale. However, the error rates of both models increase in the cross-device interoperability scenario. Evaluating the TypeNet model trained in the desktop scenario with the mobile dataset the EER increases from 2.2% to 13.7%, and from 9.2% to 21.4% for the TypeNet model trained with the mobile dataset when testing with the desktop dataset. A solution based on a mixture model trained with samples from both datasets outperforms the previous TypeNet models in the cross-device scenario but with significantly worse results compared to single-device development and testing.

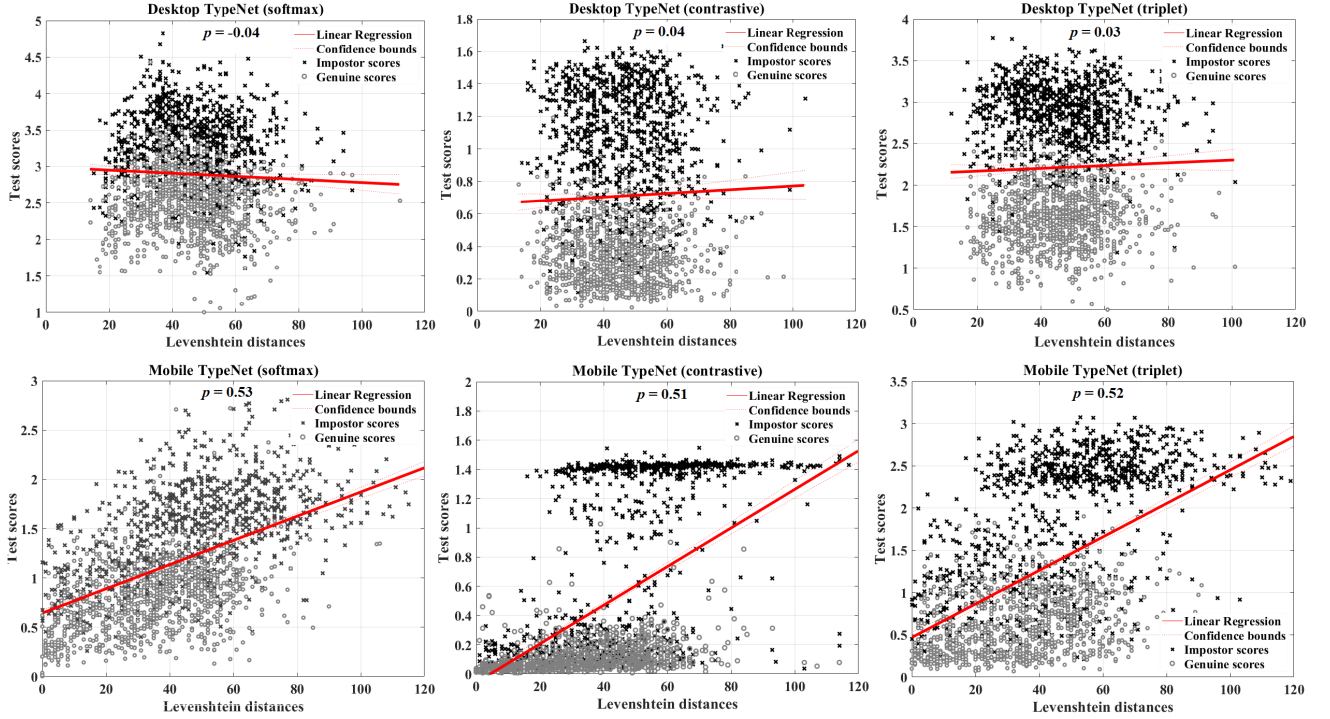


Fig. 6. Levenshtein distances vs. test scores in desktop (up) and mobile (down) scenarios for the three TypeNet models. For qualitative comparison we plot the linear regression results (red line), and the Pearson correlation coefficient p .

In addition to authentication results, identification experiments have been also conducted. In this case, TypeNet models trained with triplet loss have shown again a superior performance in all ranks evaluated. For Rank-1, TypeNet models trained with triplet loss have an accuracy of 67.4/25.5% (desktop/mobile) with a background size of $\mathfrak{B} = 1,000$ identities, meanwhile previous related works barely achieve 6.5% accuracy. For Rank-50, the TypeNet model trained with triplet loss achieves almost 100% accuracy in the desktop scenario and up to 87.5% in the mobile one. The results are improved when using auxiliary-data to realize a pre-screening of the initial list of gallery profiles (e.g. country, language), showing the potential of TypeNet models to perform great not only in authentication, but also in identification tasks. Finally we have demonstrated that the text-entry dependencies in TypeNet models are irrelevant in desktop scenarios, although in mobile scenarios the TypeNet models have some correlation between the input text typed and the performance achieved.

For future work, we will improve the way training pairs/triplets are chosen in Siamese/Triples training. Currently, the pairs are chosen randomly; however, recent work has shown that choosing *hard pairs* during the training phase can improve the quality of the embedding feature vectors [37]. We will also explore improved learning architectures based on a combination of short- and long-term modeling, which have demonstrated to be very useful for modeling behavioral biometrics [38].

In addition, we plan to test our model with other free-text keystroke databases to analyze the performance in other scenarios [39], and investigate alternate ways to combine the multiple sources of information [33] originated in the proposed

framework, e.g., the multiple distances in Equation (6). Integration of keystroke data with other information captured at the same time in desktop [4] and mobile acquisition [40] will be also explored.

Finally, the proposed TypeNet models will be valuable beyond user authentication and identification, for applications related to human behavior analysis like profiling [41], bot detection [42], and e-health [43].

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