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Quantitative assessment of similarity between randomly acquired characteristics on high quality exemplars and crime scene impressions via analysis of feature size and shape

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ABSTRACT

Forensic footwear evidence can prove invaluable to the resolution of a criminal investigation. Naturally, the value of a comparison varies with the rarity of the evidence, which is a function of both manufactured as well as randomly acquired characteristics (RACs). When focused specifically on the latter of these two types of features, empirical evidence demonstrates high discriminating power for the differentiation of known match and known non-match samples when presented with exemplars of high quality and exhibiting a sufficient number of clear and complex RACs. However, given the dynamic and unpredictable nature of the media, substrate, and deposition process encountered during the commission of a crime, RACs on crime scene prints are expected to exhibit a large range of variability in terms of reproducibility, clarity, and quality. Although the pattern recognition skill of the expert examiner is adept at recognizing and evaluating this type of natural variation, there is little research to suggest that objective and numerical metrics can globally process this variation when presented with RACs from degraded crime scene quality prints. As such, the goal of this study was to mathematically compare the loss and similarity of RACs in high quality exemplars versus crime-scene-like quality impressions as a function of RAC shape, perimeter, area, and common source.

Results indicate that the unpredictable conditions associated with crime scene print production promotes RAC loss that varies between 33% and 100% with an average of 85%, and that when the entire outsole is taken as a constellation of features (or a *RAC map*), 64% of the crime-scene-like impressions exhibited 10 or fewer RACs, resulting in a 0.72 probability of stochastic dominance. Given this, individual RAC description and correspondence were further explored using five simple, but objective, numerical metrics of similarity. Statistically significant differences in similarity scores for RAC shape and size were consistently detected for three of the five metrics (modified phase only correlation, Euclidean distance, and Hausdorff distance). Conversely, a single metric (the matched filter) expressed the least dependence between score and both shape and size. Moreover, for all crime-scene-like RACs with coincidental association in position, the matched filter produced the greatest discrimination potential in sorting known matches and known non-matches. Despite this demonstrated success, numerical metrics of similarity are not without limitations, and the remainder of this work provides commentary on the difficulties associated with using objective metrics when faced with segmentation, incomplete information, and low signal-to-noise ratios.

1. Introduction

Footwear impression evidence can be left at almost any crime scene; when present, detected, and properly collected, it can prove invaluable to forensic scientists in order to link a suspect to a scene or to assist in the reconstruction of a crime. Given the ubiquitous nature of this type of evidence, it is important to fully understand the various ways in which footwear impression evidence can be used and evaluated by analysts, including the strengths and weaknesses of each proposed approach. With this in mind, several studies have examined the utility and discrimination potential of three major aspects of footwear impressions: class, subclass, and

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randomly acquired characteristics (RACs) [1–9]. Through the use of class and subclass characteristics, an examiner may be able to eliminate an extremely large number of possible source shoes, greatly narrowing the number of reasonable leads and possible contributors in a criminal investigation [10,11]. However, to arrive at a more conclusive association between a questioned and known footwear exemplar, the examiner must proceed to compare the quantity, quality, clarity, and complexity of what are termed accidental or randomly acquired characteristics (RACs) (*e.g.*, tears, nicks, stones, holes, etc.). As such, an active area of research is how best to demonstrate the degree to which information carried in accidental features is both transferred to impressions and variable enough to correctly link known matches (or rarity) [6–9].

Much of the existing work assessing the discrimination potential of randomly acquired characteristics is affirmative in the sense that it has reinforced past assertions that source identification naturally follows from a demonstration of RAC agreement between two impressions. However, it is important to note that the majority of research is based on either theoretical data [7], high quality impressions [8,9], or small empirical datasets [6,8,9]. Moreover, the conclusion that impressions were formed by a common source is typically a function of the footwear examiner's internalized knowledge and subjective experience concerning the probability that identified randomly acquired characteristics (of a given quality and quantity) could co-exist by random chance alone [12]. However, to date, there is insufficient research to characterize the degree to which objective similarity metrics can perform similar tasks, including an assessment of the strengths and weaknesses of each metric as a function of RAC size and shape. For this reason, the research presented here characterizes, compares, and quantifies RAC loss, variation, and discrimination potential (similarity score for known non-match RACs) as a function of five simple numerical metrics of similarity.

1.1. Sources of variability in footwear impression evidence

Numerous factors impact the appearance of footwear impressions created and collected during the commission and investigation of criminal activities. Consequently, examination and interpretation of this evidence is innately challenging and requires extensive training and accumulated expertise. More specifically, the entire process tends to be influenced by variations in print creation, collection, and enhancement, and in order for analysts to reasonably compare crime scene impressions to high quality exemplars obtained from suspect shoes, it is imperative that the sources of variability be understood and accounted for.

1.2. Creation of crime scene impressions

Despite the numerous methods of crime scene print creation, there are two major classes: two- and three-dimensional. Within each of these classes, however, exist a number of different factors that can contribute greatly to the variability present in the appearance of crime scene shoeprints.

Two-dimensional impressions include those that sit on top of a surface and have no discernible depth [13]. Positive impressions result from a transfer of material from the outsole to a substrate; examples include prints in blood, grease, and dust [10]. Conversely, a negative impression is left when an outsole lifts a residue from a surface. These often occur when a clean shoe comes into contact with a dirty surface and removes accumulated dirt or dust from the substrate. For negative impressions, the outsole elements are depicted in the void pattern. Clarity and quality of the impression often depend on the surface of deposition (*i.e.*, a waxed floor tile will likely capture a more detailed impression than carpet) as well as the media in which the print is made (*e.g.*, blood, grease, dust, etc.) [13].

Three-dimensional impressions result in deformation of the surface, producing an impression with depth. These prints can be found in soil, sand, and snow, and the detection, preservation, and forensic utility of these impressions vary depending on a multitude of environmental conditions, including substrate composition [14,15].

1.3. Collection and enhancement of impressions

Given the variability in the initial appearance of footwear impressions, the methods for collecting and enhancing this evidence can differ greatly depending on the conditions of deposition. For example, in addition to photography, two-dimensional prints are lifted [16–18] to improve visibility and allow for further examination, while three-dimensional impressions are often cast in order to preserve the entire depth of the impression [19,20].

In addition to collection of crime scene prints for examination, enhancement methods may be employed to maximize visual detail. In general, impressions can be enhanced in four major ways: chemically, physically, digitally, or optically. In order to increase contrast between the impression and the background, chemical methods are carefully selected depending on the material on which the print is deposited, as well as the properties of the media. Extensive research exists detailing which methods are appropriate in a variety of scenarios [18,21–25]. Likewise, physical enhancement can be utilized to maximize contrast. This technique typically involves increasing contrast via the use of a physical addition to the print, such as the application of powder [10]. For example, by applying an opaque or fluorescent fingerprint powder to an impression on a waxed surface, the evidence will retain the powder and can be easily distinguished from the background. Alternatively, digital enhancement techniques can be used alone or in conjunction with another technique. These methods aim to use computer algorithms to increase image quality by maximizing the signal-to-noise ratio, thus increasing the amount of information available to the analyst for comparison purposes [26,27]. Lastly, optical enhancement includes the use of specialized light sources (*e.g.*, ultraviolet, infrared, etc.) to maximize contrast of the impression against the background and therefore increase the clarity and detail of evidence [28–30].

Given the inherent variability and complexity of footwear impression deposition, as well as the number of physical factors that can influence replication (*e.g.*, media, substrate, pressure, etc.), it is reasonable to expect variability in the appearance (clarity, quality, detail, etc.) of crime scene evidence. In short, a crime scene impression will rarely be an exact replicate of the source shoe or a corresponding high quality exemplar print. More specifically, the RACs which are visible in a high quality image are unlikely to consistently reproduce in crime scene evidence impressions. This is especially true given that RACs show variability in reproduction among high quality replicates even when prepared under ideal conditions in the laboratory! In fact, to account for this inherent variation, several replicate exemplars are typically created under controlled conditions for both case and research purposes [5,8], which further exemplifies the need to better understand RAC variation as a function of shape, perimeter, and area. Moreover, the experienced human observer seems to be innately equipped to recognize the origin of these variations; and when the variations are within reason, he or she can still effectively mate known matches in the presence of incomplete information, distortions, and low signal-to-noise ratios. However, this is not necessarily true for simple numerical metrics which are more adept at evaluating the *faithful (or exact)* reproduction of features, rather than estimating the number of ways a single feature may reproduce under an infinite