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Interpol Review Paper of Marks and Impression Evidence 2019-2022

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ABSTRACT

This section contains an overview of publications relevant to advances in scientific methods and general discussions concerning shoe and toolmark examiners, which were published between January 2019 and May of 2022 and is the sequel to the review for the 19th Interpol International Forensic Science Managers Symposium in 2019 by Martin Baiker-Sorensen. A literature search was conducted covering relevant articles published in the main forensic journals:

1. Shoemarks

1.1. *Determining demographic information from shoemarks*

Shoemarks can be used as an investigative tool to narrow the population of people who may have left a shoemark at a crime scene. The most common and obvious starting point is to evaluate the appearance of the overall tread design in the shoemark left at a crime scene with those observed on the bottom of shoes in the possession of a suspect. An investigator may be able to glean some useful information about their suspect(s) description by evaluating the characteristics of the shoemarks left at their crime scene. A recent study showed that a correlation between stature and foot measurements [1] could be made using seven dimensions taken from the main part of the foot. Volunteers consisted of randomly selected anatomically healthy adults consisting of 85 men and 17 women between the ages of 20 and 66. After their height was measured, the volunteers placed their feet on a glass-topped table and images of their feet were captured using a digital camera placed beneath the table. The images were processed to adjust rotation, place landmarks, and perform the measurements. The obtained data was processed, and correlation coefficients were calculated to determine the correlation significance between stature and foot measurements. It was demonstrated that five of the seven measurements had a high correlation with the stature for the test group. It was noted that the small number of women in the study prevented a meaningful comparison between sexes and created an imbalance that influenced the resulting correlation coefficients.

An additional study evaluated the use of partial shoemarks to determine the length of the shoe responsible for a shoemark which in turn, would provide investigators with the approximate size of the shoe investigators would be looking for. Shoe length can be used as one of the important class characteristics of imprint or impression evidence to convict suspects in the court, as different people have different shoe sizes. As a basic and vital characteristic, shoe length can easily be determined from a complete shoeprint. However, shoeprints found at crime scenes are usually incomplete, distorted, or obscured. One study set out to attempt to determine a shoes length from partial shoeprints [2]. Four feature points were defined and named, respectively, as tiptoe, lateral metatarsal, heel, and medial metatarsal. Six different lengths are defined between these four points; mean values of measurements on left and right shoeprints were employed for analysis to minimize deviations caused by subtle differences when selecting the feature points.

Three kinds of regression analysis were performed (linear, quadratic, and cubic) to study the correlation between the six different lengths. Among the three regressions, cubic was chosen to be the optimal equation. Through analysis of test prints involving nine volunteers walking on flooring and in sand, 5 cubic regression equations were obtained, one for each length between the four feature points on the outsole (not including the shoe length from tiptoe to heel). These equations were applied to 2 different cases and showed reliable results with a relatively low error between 0.288 and 0.534 cm. For one of the measurements the error was 3.795 cm, which the authors attribute to the peculiar shape of uncommon or special shoe types.

The authors summarized their findings by noting that shoe length can be estimated through the equations provided if at least two of the four feature points can be obtained. This study is limited to the shoe types that were used in the study and should not be used for specialized shoes such as athletic cleats or similar shoes with highly pronounced design elements.

Another example of information that may be derived from shoemarks at the scene is Forensic Gait Analysis. A recent study [3] discussed forensic gait analysis as a method of forensic identification. When

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applied by individuals with experience in areas such as biometrics and clinical gait analysis, forensic gait analysis is defined as "the recognition and comparison of gait and features of gait, to assist the process of identification." However, it is the opinion of the authors that "forensic gait analysis currently lacks a standard method and criteria for analysis and interpretation, and implicitly, sufficient peer-reviewed publications to validate current methods, especially in cases where the forensic gait expert tackles poor-quality footage." As a result, the authors caution that the "courts should treat gait evidence with caution, as they should any other form of evidence originating from disciplines without fully established codes of practice, error rates, and demonstrable applications in forensic scenarios."

1.2. Acquisition and enhancement of shoemarks

The ability of an examiner to associate or disassociate shoemarks with a shoe is often most dependent on the quality of the shoemarks documented and collected at the crime scene. A shoemark may contain Randomly Acquired Characteristics (RAC's) suitable for identification or elimination, but if the shoemark is not documented or collected in a manner that will exhibit the RAC's with sufficient clarity for the examiner to evaluate, then the examiner may be left with a less meaningful conclusion in the end.

One method to image shoemarks that is being explored is the use of high-resolution automated 3D imaging (Liao et al., 2019), where the history and shortcomings of previous 3D image acquisition systems are summarized before presenting a newly developed system. This new system is more affordable than commercial systems, easier to operate, and is more robust. By using a 3D image capture system, impression images can be collected in a non-destructive way that requires less time and money than other collection methods and creates digital files that can be shared with other examiners. The new system is based on the digital fringe projection (DFP) technique, which the authors explain in great detail. The prototype system comes in 2 different resolutions: the low-resolution system achieves 137 dpi with a field of view of 14" x 8.75" and the high-resolution system achieves 400 dpi with a field of view of 5.12" x 3.84." The article contrasts a commercially available system to both prototype systems by comparing close to a dozen different scenarios, such as: light or dark shoe bottoms, colored and rounded surfaces, impressions in sand, soil, clay, and snow, and direct comparison to conventional 2D photographs and casts. In all tests, the high-resolution system performed as well or better than the commercially available system while also being cheaper, easier to use, and more customizable. The advantage of the low-resolution system is the larger area captured in one image. Further research will integrate stitching software for the high-resolution system.

Recovery of 3D shoemarks is examined further in a study [4] where shoe impressions were made in both sand and soil. Traditional 2-D photography, casting, and Structure from Motion (SfM) photogrammetry were used to capture the impression, recovering the class characteristics and the RACs. Results show that SfM photogrammetry provides better visualization in most cases, with traditional photography a close second. Casts were superior in showing shallow damaged areas that were not visible in traditional 2-D photographs. Adding SfM photographs to traditional photography would be beneficial to crime scene examiners, as it only requires several minutes of additional work.

A SfM photogrammetry software was evaluated to determine its ability to reliably capture 3D impressions [5]. The vast majority of three-dimensional impressions are captured using traditional methods including two-dimensional photography and casting. The reliability of 3D capture methods that use (SfM) photogrammetry is something that is being evaluated for use in capturing footwear evidence. The output of this technology is a digital three-dimensional point cloud of the impression. Larsen and Bennet set out to examine the reliability of photogrammetry to capture the same data when repeatedly used on one impression. They also set out to evaluate the impact of variability between models. They found that there was little variability when comparing cloud to cloud measurements which implies that there is accuracy and consistency in using these techniques to capture three-dimensional impressions. Using this method, three-dimensional impressions can be collected with a repeatability of 97%. They found that the more uniform the color of the impression, the closer the point clouds map to one another. In terms of substrate influence, snow had the largest disparity between clouds in this experiment. The use of contrast increasing sprays and controlling the light around the impression may be required to increase reliability with respect to impressions in snow. It should be noted that the authors indicated one of the limitations surrounding this study is that there were only two participants.

The use of SfM photogrammetry was further explored to evaluate the ability to recover latent footwear impressions in polypropylene carpet [6]. SfM photogrammetry was shown to be a useful compliment to existing techniques, offering information about the size and sole design features of the responsible footwear, and suggesting that it could be used to document the movement of an individual at a crime scene for reconstructive purposes. The authors suggest that this technology also proved to be successful at documenting individualizing RAC's. The study showed that significant details can be recovered from footwear impressions left in polypropylene carpet and that, undisturbed, the impressions can remain for over a month. This technique also proved useful in documenting barefoot impressions, providing three-dimensional models that allow a more statistical approach to be taken to compliment expert opinions in forensic podiatry.

Examiners have many ways of collecting bloodstained footwear impressions, but most of these techniques are destructive or lack the quality needed to perform a comparison. A study [7] used a noncontact, nondestructive method of detecting and analyzing bloodstain impressions. Ideally, such a method would be highly sensitive (even when dealing with dilute bloodstains) and highly specific (to avoid false positives). Hyperspectral imaging (HSI) is one such technique that is well established and has been applied to bloodstains and fingermarks before. When using an HSI camera, several sets of images are recorded for narrow ranges of wavelengths in the electromagnetic spectrum, then combined to form a "three-dimensional hyperspectral data cube."

The experiments involved in this study use a commercial HSI system (SPECIM IQ) and a DSLR camera to compare bloodstains on tiles, laminate, and carpet, all of different colors. Several dilutions of blood were used for each impression to a max dilution of 1:50, and successive footsteps were made to "deplete" the amount of blood in each impression. Throughout the study, the HSI system consistently recorded more data at different dilutions, depletions, and substrates. The added benefit of using a hyperspectral camera, set up as described in the article, is that pixels identified as blood are black while all other pixels are white, which provides a noncontact method for blood identification and enhances the detail found on footwear tread.

Luminol is routinely used for detecting the presence of blood by its peroxidase-like activity. Some luminol-based blood detection products were developed to overcome some of the limitations of luminol including low intensity light emissions, the need for complete darkness to photograph the reaction, and the rapid decay of observed luminescence requiring multiple applications. However, many agencies still use luminol due to its reduced cost. The focus of one study [8] was to improve the capabilities of luminol by developing a formula that does not require total darkness, would provide a longer lasting and more intense luminescence, and would provide better contrast. A working solution consisting of 30 mL of a stock solution (0.1g of 3-aminophthalhydrazide in 10 mL ammonium hydroxide diluted with 100 mL distilled water) mixed with 2 mL of 3% hydrogen peroxide was prepared. Various fluorescent highlighter inks and dyes were added to the luminol formulation, and their overall effectiveness was determined by evaluating their effect on intensity, duration of luminescence, visibility in dim conditions, and change in color. The findings of the study suggest that the addition of fluorescein and the yellow and green Sharpie highlighter inks had the greatest overall effect on these parameters.

One of the challenges facing examiners is that they are often asked to compare photographs of impressions from crime scenes where the impression may be obscured by the substrate the impression is on or in. In one case example [9], crime scene investigators found two men's bodies showing significant signs of stab wounds and abrasions. A suspect was also found nearby covered in bloodstains and bruises. The crime scene team was able to collect several footwear impressions in blood and took photographs of them before and after processing with amido black. When the photographs were developed, it was discovered that the coloring of the amido black made the footwear impressions blend in with the dark pattern of the flooring, thus obscuring the impressions. The laboratory decided to digitally process the photographs in an attempt to increase the quality of the footwear impression photo. By using Adobe Photoshop's RGB color model and Channel Mixer, the laboratory was able to reinforce the shoeprint image and subtract the background color that was interfering. As a result, the footwear examiners were able to achieve an identification with the suspect's shoes recovered at the scene. This case study highlights two important techniques that should be included in any footwear examiners training; the importance of photographing impressions prior to chemical processing, and familiarity with digital photo processing programs, particularly those that deal with color balances.

Some areas of the world are faced with attempting to document or recover shoe or tire impressions in snow. In some circumstances, they are further challenged to recover shoe or tire impressions in snow that may be lost or destroyed after being covered by additional snowfall. Since the original impression in snow is compacted, the subsequent layer of uncompressed snow need only be removed to reveal the original impression. One particular case [10] used a cordless leaf blower to remove uncompacted snow from the original impression without significant degradation of the impression. After enhancement, the impression could then be photographed and casted. The author recommends a stepwise approach when employing this method of enhancement. One should photograph the impression throughout the enhancement process in case attempts at additional enhancement result in damage to the impression. Conversely, high substrate temperatures pose a different type of challenge in attempting to collect 2D impressions. One study [11] compared the performance of three different lifting methods (adhesive, gelatin, and vinyl static cling film), collecting shoe sole impressions in dust from hot flooring substrates (ceramic tile, galvanized metal, and laminated wood flooring). Dust prints were left on the substrates for 5 h on a summer day (highest temp recorded was 31.5° C, or 88.7° F). The dust prints had five class characteristics and two RACs. Results show that adhesive lifts performed the best among all substrates, with gelatin being a close second. Vinyl static cling performed the worst with poor recovery of marks and some shrinkage of the lift.

Impressions containing salt residues can be challenging to document. One study [12] presented an application method using silver nitrate solution in combination with ultraviolet light for the visual enhancement of footwear impressions containing salt residues on various substrates. Impressions containing salt residue routinely lack acceptable contrast when located on light-colored surfaces. Other methods of enhancement have demonstrated inconsistent results especially on porous surfaces or they are undesirable due to their toxicity. A solution of 5% silver nitrate in 10% methanol proved to be the best concentration for enhancement. Impressions were further enhanced by exposing them to 365 nm ultraviolet light up to a total of 30 s to produce consistent and reliable results. Although this method was not equally successful on all the substrates tested, it provides a portable, safe, and effective technique to reliably enhance salt containing footwear impressions on a variety of substrates routinely encountered at crime scenes.

1.3. *Automated mark retrieval and comparison*

Technology is always changing, and in some ways advancing many of the forensic disciplines. With respect to footwear and tire track impressions, one focus has been to use technology to create databases for examiners and investigators to identify relationships between questioned impressions and known shoes as well as databases to search questioned impressions with the hope of identifying the make and model of shoe investigators need to be looking for. A handful of commercial databases exist that allow examiners to potentially identify the make and model of footwear impressions left at crime scenes. To compliment these, public databases of footwear impressions from simulated crime scenes are also available and can be used for training purposes. One paper [13] expanded upon the publicly available sets by describing the creation of additional high-quality and simulated crime scene impressions. A selection of 87 shoes housed at West Virginia University were cleaned and documented before test impressions were created and digitized at a resolution of 600 PPI. Test impressions were created in dust and blood on ceramic and vinyl tiles. In total, 214 high-quality impressions of shoe outsoles were created (87 shoes with replicates and 40 additional close non-matches), 138 dust impressions (46 with 3 replicates of each), and 73 blood impressions (24 outsoles with 3 replicates and one additional replicate). The database includes enhanced and unenhanced images within each set for a total of 597 simulated crime scene/known test impressions in addition to the outsole scans. This database is available for public use at http://4n6chemometrics.com/Downloads/WVU2019/.

One database was created to evaluate a dataset of digitized RAC's to evaluate their rarity in an attempt to strengthen shoeprint evidence [14]. The authors created a database consisting of over 13,000 RAC's from approximately 400 shoe sole test impressions. The location, orientation, and shape for each RAC was collected. Uncertainty measurements were collected for the location, orientation, and shape of each RAC, and finally estimation of the probability distribution for each feature. The three probabilities (shape, location, and orientation) for each RAC were multiplied. The results were used to create a rarity score, using the statistical algorithm SESA (Statistic Evaluations of Shoeprint Accidentals). The scores were found to correlate with real casework. Future studies researching the variability of RACs on crime scene prints, investigating shoe sole pattern, wear, and size, and developing statistical model evaluating dependence among RACs on a shoe sole are suggested.

Another study [15] created Known Match (KM), Known Non-Match (KNM), and Known Close Non-Match (KCNM) datasets of shoe impressions using pristine impressions (using Everspry EverOS scanner impressions), and another dataset for KM, KNM, and KCNM using mock crime scene examples that more closely resemble casework. Marks were annotated on both Q and K samples, using Adobe Photoshop, and are aligned using an algorithm. Other algorithms then computed outsole pattern scores (using outsole design, size, and wear) and individual RAC scores, which were compared to the relevant KM, KNM, and KCNM populations. Comparison scores from each stage were combined into a final score by computing a score-based likelihood ratio for each type of score and multiplied together to obtain a final score. Scores were compared against the relevant populations to see where they fall in the KM, KNM, or KCNM populations. For the pristine samples, there was more separation between the KM and KNM populations. The mock crime scene datasets had less separation. Further research is ongoing.

1.4. *Examiner performance factors*

One of the primary areas of focus in research relating to impression evidence is examining an examiner's ability to distinguish between class characteristics and unique characteristics (RAC's), and in the external and internal influences that an examiner may encounter during the course of their duties and the affects these influences may have on their ability to reach the appropriate conclusion(s). One study examined the impact of contextual information on decision-making [16]. Twenty-three forensic footwear examiners performed an examination of 22 sets of shoeprints images. Each set contained a questioned shoeprint, a known test shoeprint, and a known outsole. The sets were broken into two sessions: one with 11 sets (5 matches, 6 non-matches), and another with 11 sets (5 matches, 6 non-matches). Three image sets were flipped horizontally and "repeated" in the other session. Each examiner was given the instructions on the screen (media, substrate, and prior examiner conclusions, and type of crime). After completing a set, they were asked to provide their conclusion and to rate the difficulty of the examination. In the second set, extraneous context was added to the instructions, with everything else remaining the same. The Tobii®X3 eye tracker and its supporting software, Tobii Studio, were used to record the examiners' eye gaze. Metrics measured were total fixation duration referring to the sum of the duration for all fixations within an area of interest group, the fixation count referring to the number of times that an examiner fixated on an AOI group, and the average saccade amplitude referring to the distance between the earlier fixation location and the current fixation location. Results show that examiners fixated more on the question print more after receiving the extraneous context, and that the comparison strategies and visual search patterns changed. After exposure to the extraneous context, the consensus and accuracy rate increased, and examiners also perceived that the task was more difficult. In summary, this study shows that contextual information does influence the examiner's decision-making process but having verifications in place will reduce false negatives and false positives. The risk is if the identification conclusion of the first examiner will duly influence the conclusion of the second examiner.

The impact of fatigue on decision-making was also examined in footwear examinations [17]. The impact of fatigue has been studied in many disciplines, but little research exists regarding fatigue on performance in footwear examination. This article tries to gain a better understanding of whether footwear examiners make different conclusions and whether eye tracker software is a useful tool in assessing examiner performance of footwear examination. The study included 12 trained footwear examiners with 5 to 25 years of experience. 23 volunteers were asked to wear shoes of four different outsole patterns to create 50 pairs of known and questioned shoeprint images for the study. The study was done in two sessions, one in the morning (low fatigue) and the other in the afternoon (high fatigue). 10 image sets were in both sessions but flipped horizontally in order to study if examiners reached the same conclusion while also removing memory bias between the morning and afternoon sessions. Of the 120 data sets that repeated in each session (12 examiners x 10 repeated image pairs), the morning session data resulted in 8 matches being erroneously excluded and 17 non-matches being erroneously identified. In the afternoon, 25 matches were erroneously excluded, and 34 non-matches were erroneously identified. Through statistical analysis, the authors show that there is no significant difference in the conclusions reached caused by fatigue.

Eye tracker software also showed no significant effect caused by fatigue recorded over three different metrics. The study dives deeper into analysis of search patterns in image pairs between morning and afternoon sessions. In general, it was found that fatigue does not have a significant effect on the search patterns of examiners.

The need for developing a quantitative approach to evaluating footwear comparisons has been expressed in the forensic community. This is particularly important when considering shoes of the same design and size where the examiner must use wear patterns and perceived Randomly Acquired Characteristics to make an opinion. One study [18] used correlation-based metrics to evaluate the discrimination ability between close non-matches observed in three different sets of impressions provided by Everspry Scanner Impression data from 10 shoes, FBI boot impressions from 72 boots of the same make and model, and the West Virginia University footwear impression data from 36 shoes consisting of several different outsole designs. Normalized Cross-Sectional (NCC), Phase-Only Correlation (POC), AvNCC, and AvPOC were used to evaluate their ability to discriminate between impressions made by a shoe of interest and other shoes that are considered to be close non-matches to the shoe of interest. Close non-matches were defined as two different shoes of the same make, model, and size. The results of this study indicate that Phase-Only Correlation performs as well as or better than the other metrics that were considered. The results of this study showed that Phase-Only Correlation also worked well with impressions in blood and blood with the application of Leucocrystal Violet as an enhancement technique. It was noted that Phase-Only Correlation performed poorly with dusty impressions.

In an extensive 19-month study [19], 70 examiners each performed 12 comparisons and reported a total of 835 conclusions resulting in a dataset that includes more than 1000 examiner attributes. The study focused on determining the degree to which different types of features were identified, evaluated, and weighed before arriving to a conclusion of association or disassociation between questioned and test impressions. Results of this study indicated that there was considerable variation in feature identification and annotation with higher consistency in the reporting of examiner conclusions (85.6%), which is in alignment with similar studies that have been performed.

The study was further expanded [20], and examiners were assessed on the accuracy of their conclusions based on three criteria: (1) inherent agreement and disagreement in class, wear, and randomly acquired features, (2) limitations as a function of questioned impression quality and clarity, and (3) the examiners adherence to the SWGTREAD 2013 Range of Conclusion Standard. The authors astutely pointed out that it is difficult to evaluate accuracy when there are seven different conclusions and only one ground truth answer. With this in mind, based on ground truth and the adherence to the SWGTREAD (2013) conclusion standard, the expected conclusion was reached an average of 83% of the time. The authors recognized that there are limitations in reporting the statistical evaluation of the conclusions when using a range of conclusions that has seven different choices for the participants. They noted that the results would inherently differ if a smaller range of conclusions was used, such as a three- or four-point scale commonly used by other forensic pattern disciplines. The third summary of this series compared the results presented with those collected in other forensic pattern sciences using three-point conclusion scales. The third publication [21] in this 3-part series involving the 19-month study summarizes the Predictive Value (PV), error rates, and Inter-Rater Reliability (IRR). The correct predictive value varies from 94.5% for exclusions, 85% for identifications, 70.1% for limited associations, and 65.2% for association of class characteristics. Incorporating ground truth, the case study shows a false-positive rate of 0.48%, a false-negative rate of 15.6%, and a positive predictive value of 98.8% and a negative predictive value of 93.3%.

1.5. Randomly acquired characteristics

Several studies evaluated reproducibility of RAC's and the quality of the RAC's within the replicates. One study [22] evaluated 55 outsoles which were worn by 33 volunteers. Dust impressions were lifted using magnetic powder and a self-adhesive lifter. The impressions were taken at different intervals over the course of 6 months. 1447 dust impressions were collected, with 18,747 pairs of same source samples among them. The prints were segmented into grids using Photoshop CS6, and the presence/absence, angle, and density of the General Schallamach Pattern (GSP) were measured. An algorithm was developed to compare the impressions. This study showed that the discriminating power of the GSP was approximately 79% with sample pairs lifted within one day and ultimately demonstrated that GSP's can be distinguished from one another, primarily in the heel part of the outsole.

In a similar study [23], the authors examined randomly acquired characteristics (RAC), specifically cuts to the heel of shoes with rubber outsoles, to determine how long these characteristics persist and how they change over time. The study included 42 individuals wearing shoes with rubber outsoles of the same design. The researchers placed one artificial cut, similar in size and position, on the heel area of each outsole. Dust impressions were made for each outsole and then a high-resolution scan of each impression was created. Using Photoshop, the areas representing the artificial cut were outlined using the magnetic lasso tool, painted red using the brush tool, and saved as a separate image. Using Fiji software, 20 measurements were made of each artificial cut area to adequately characterize its shape and location on the outsole. These measurements were used to evaluate how the artificial cuts changed over time. Through the use of a Support Vector Machine (SVM), "a generalized linear classifier used to classify linearly non-separable and high-dimensional data" the researchers could classify two different cuts as "same-source" or "different-source" cuts. The experiment showed that cuts of similar size on the heel area of rubber outsoles were relatively reliable acquired characteristics for the duration of the study (6 months) and the use of SVM proved to be an effective classification method. Future studies investigating the effectiveness of SVM with smaller and real RAC's are suggested.

The reproducibility and the quality of the impression can be difficult to determine due to a variety of factors, including examiner subjectivity in the evaluation of the marks. One study [24] sought to develop a reproducible and quantifiable framework to assess the quality of questioned footwear impressions. The authors noted that there are currently no standardized quality metrics that can be relied upon to grade footwear impressions. Therefore, the authors developed a novel footwear-specific rubric as a method of assessing the quality of impressions. This rubric can be applied to footwear impressions submitted for examination or for evaluating the suitability of footwear impressions for use in validation studies. The authors offer this framework as a potential basis for standardization for assessing the quality of questioned impressions and developing common vocabulary when assessing or describing footwear impressions. The authors also note the potential for this framework to assist in the development of automated footwear impression quality assessment algorithms.

Another consideration is the variability in an examiner's conclusion scale used across the pattern disciplines. The conclusion scales vary from discipline to discipline for a variety of reasons including, the nature of the source of the pattern being made by a manufactured item or naturally occurring such as with friction ridge. The strength of the conclusion is also based on the body of research for each of the disciplines and may be affected by the experience of the examiner(s). One study [25] set out to evaluate the strength-of-support conclusion scales for fingerprint, footwear, and toolmark impressions. Participating forensic examiners each conducted 60 casework-like comparisons in their discipline using images. On each trial, they were told to use either the traditional scale of conclusions or a scale based on strength-of-support language. For the purpose of this summary, only the footwear portion, in which 32 examiners participated, will be discussed. Half of the trials used shoes that were the same make and model purchased by a runner who wore them to approximately the same level of wear. The other half of the trials consisted of shoes and light hiking boots (at least two pairs of the same make and model) and had been moderately worn. Only heel impressions were used for the study. Results show a total of five erroneous identifications outcomes. The study shows that there were no large differences between the two conclusion scales being used, with perhaps a light drop between High Degree of Association and Strong Support for Common Source. The two scales seemed to be treated more equally among the footwear examiners. This may be because the existing footwear articulation is more similar to the strength-of-support scales because it includes language of "degree of association" rather than statements about source.

1.6. Case report

One case report [26] described the examination of a victim whose head was potentially run over by a vehicle tire. Byard described "distinctive black patterned markings present" on the left side of the victim's head and face. Byard went on to opine that these marks "corresponded to the pattern of tire tread taken from a vehicle identified by police" and that the "photographs of the tires were compared with the markings on the left side of the face that were identified at the scene and autopsy, showing a close match." It should be noted that this case report was submitted to the pathology/biology section of the Journal of Forensic Science and as such, the significance of the opinion of "a close match" was not clearly defined. Footwear examiners would typically choose one of the levels of conclusion proffered in the SWGTREAD or similar conclusion scale to express their assessment in a report or during testimony. The author offers some sage advice to make every effort to photograph and document transfer pattern markings from tires left in a foreign material such as oil, dirt, and rubber on a decedents head prior to them being transported from the scene in a body bag. This would aid in rendering the best evidence for comparison before it is potentially altered or destroyed.

1.7. Technical report

A technical report [27] containing suggested standards for the scope of work relating to footwear and tire track examiners. This technical report covers the primary responsibilities and duties of a footwear/tire examiner. By omission, it describes the types of examination that should not be performed by someone in this role. Responsibilities include determination of make, model, or manufacturer of the source of a questioned impression, comparisons, writing reports, and providing expert opinion regarding conclusions. The main duties include detecting, preserving, collecting, recovering, and documenting footwear or tire evidence; preparing test impressions; enhancing impressions for analysis and documentation; and providing verification of findings.

2. Toolmarks

2.1. Toolmarks in bone and cartilage

One of the more prominent toolmark research topics published over the last couple of years has been related to toolmarks in bone or cartilage. Due to the nature of homicides using a blunt or sharp object, toolmarks have a high potential to be transferred to these types of tissues and can often be recovered and used for a comparison.

Saws of various forms were discussed in multiple papers related to bone and cartilage. In this first paper [28], the authors explore the different cut surface characteristics left on bone using three different types of hand-powered saws (Hacksaw, Tenon Saw, and Jr Hacksaw). They detailed and assessed 10 different characteristics produced by these saws (cut surface striations, striation regularity, cut surface polish, pull-out striae, tooth hop, harmonics, breakaway spur, breakaway notch, entrance shaving, and exit chipping). To produce test cuts, they selected de-fleshed juvenile pig radii. To make the hand-powered cuts more consistent, they time each stroke using a metronome and made by the same researcher. These cuts were also made with the bone being secured in a vice to control the cut and removal of the saw. Each saw was used to make a total of 14 cuts for a total of 42 cut surfaces evaluated in this study.

The results of this study revealed a few characteristics that demonstrated no differences between saw type and the resultant toolmark. All three demonstrated no difference in cut surface striation shape, cut surface striation regularity, harmonics, and exit chip pattern. Using appropriate microscopy, it was also observed that all of the three saw blades produced straight, non-uniform striation patterns. Statistically, the only evaluated feature that was different between any of the saws was the cut surface polish. The handsaw (featuring an alternating blade) had a cut surface polish on 92.9% of the samples while the junior hacksaw had this displayed on only 21.4% of the cuts. While not statistically significant, there were five other characteristics that demonstrated some variability between the blades: entrance shaving, breakaway spurs, breakaway notches, pull-out striae, and tooth hop. While there are some data sets within this study that are interesting, the author suggests further research be conducted on the variability between users of the hand-powered saws, how these saws interact with human bone versus porcine bone, and a wider selection of saws. These studies would help to contribute more information about the ability to identify the different classes of saws in bone material based on the resultant toolmarks.

While the previous study looked at many different characteristics, a couple of other studies were published that looked at some specific characteristics when it comes to toolmarks in bone. In one of those studies, the authors looked specifically at false start kerfs (FSK) to evaluate the correlation between kerf and saw blade width (Menschel et al., 2020). This study utilized White-tail Deer bones (humerus, radius, tibia, and femur) which were found to be more similar to human femur bone density compared to juvenile pig or sheep bones. Sixteen saws (11 manual-powered and 5 mechanical-powered) were selected for this study. The authors also included both new and used saws. The authors made toolmarks (false start kerfs or FSKs) using all 16 saws in the bone with the test bone being restrained in a vise. Some of the saw types were used to make multiple marks dependent on the saw type. Another set of FSKs were made using only some of the manual-powered saws while the bone was minimally restrained by hand when safe to do so. The entire experiment yielded a total of 496 FSKs between the different saws, repetition of marks, and different methods of securing the bone.

The authors summarized the study by detailing that blade width, saw power, and restraint condition has a significant effect on the minimum kerf width (MKW). The author also found that the general rule that the MKW does not exceed 1.5 times the blade width to still be generally true. While there was significance in these areas, the author ultimately urges examiners not to rely on only one factor when looking to limit the saw type that was used in a crime.

A second author looked at the measurements of a saw's tooth per inch (TPI) [29]. This study explored the differences in bone from different species and the ability to accurately measure tooth hop. Two new saw blades (both being 7 TPI; one with a beveled carbide crosscut-style teeth and the other with flat, untreated, rip-style teeth) were used for this experiment. Those saws were used to cut human and deer femora, as well as pig humeri that had been frozen fresh and allowed to defrost prior to sawing. A total of 1766 tooth hop measurements were taken and 193 measurements of the distance between teeth on the saws themselves.

The study found that there was some difference between the bone type and the tooth hop measurements. Within the study, the author noted that there was significant wear of the blade affecting the DBT (distance between teeth) as well as a significant difference when comparing the DBT to the tooth hop in the toolmark. The author suggests that an increase of plus or minus 2–2.5 TPI should be used when there is a small sample size on evidence, though their data was all within approximately plus or minus 1.5 TPI. The study also suggests that the use of pig and deer proximal limb elements are a suitable substitution when replicating tooth hop measurements.

In a third study relating blade size back to the toolmark, these authors used 38 new saws that featured a variety of profile shapes and designs [30]. This sampling included reciprocating saws, hacksaws, and hand powered saws. These saws were used to create ten false start test cuts each. This study stands out from the other saw studies as the authors used fleshed human limbs to create the test cuts instead of defleshed human libs or other animal materials. The authors of this paper utilized an imaging technique known as Micro-Computed Tomography (CT). This technique takes thousands of 2D radiographs from the sample and reconstructs it to form a full 3D model.

The use of the micro-CT was found to be useful within this study and particularly for documenting false start toolmarks. The authors found that there is a possibility in accurately predicting a saw blade thickness from false start toolmarks within 2 standard deviations. This study acknowledged their use of older human limbs is still a variable that has not been explored since a younger human bone may respond differently.

While not about the characteristics themselves, the authors of another paper demonstrate a way of documenting saw marks in bone [31]. They discuss the advantages of using Reflectance Transformation Imaging (RTI) when analyzing and documenting saw toolmarks in bone. By using this imaging system, some features were visible that could not be photographed using regular oblique lighting in a single photograph. The versatility of this imaging system can assist the examiner in producing images that better display the toolmarks present on a saw toolmark in bone.

While many test materials have been discussed in the previous articles so far, the authors of one study specifically tested this variable [32]. Due to a variety of legal and ethical factors, human bone may not be available for producing comparison samples for a crime involving a saw used to cut a bone or dismember a human. The authors explored a commonly used substitute material, porcine bone. This study looked at bone type and age of the pig that they came from evaluating the bone hardness from different portions and sides of the bones. Some significant differences within the age of the bone and between the bone type (femur or humerus) were found. The authors cite previous research on human bone in their discussion but did not directly experiment with human bone themselves in this study.

2.2. *Casting toolmarks on bone and cartilage*

There were many studies that looked at the toolmark characteristics in bone and cartilage, but this study looked at how best to preserve, collect, and create toolmarks for comparison purposes [33]. One of the first topics explored is a way of effectively performing a fixation process, using paraformaldehyde or formalin, on cartilage to limit the size and distribution of “dots” in the casts. The authors hypothesize that these dots are formed when the casting material fills the lacunae of the chondrocytes. They conducted experiments by fixing the cartilage samples in different fixatives at different time intervals. Their experimentation determined that there was no difference in the size and distribution of these dots between the unfixed cartilage and either of the fixation treatments up to 90 h.

The second aspect the authors explored was the color of casting material and the ability of the analyst to visualize toolmarks using both light microscopy and the ToolScan 3D toolmark scanner. For this experiment, they used various colors of many different brands of casting materials. The most notable result of this portion of their study was that many different colors (blue, green, white, and grey) did not perform well, if at all, using the ToolScan system. The author found that the brown casting material scored best with light microscopy while the black casting material faired best using the ToolScan system.

The third variable the authors studied was the type of materials used for producing test marks for comparison. Six different materials were evaluated, and agarose was found by the authors to perform well in its ability to record and reproduce individual toolmarks. The safety aspect of the non-hazardous material and ease in which test marks can be made make agarose an excellent test material for producing known samples.

2.3. *Case studies involving toolmarks in bone or cartilage*

Along with interesting research in the world of toolmarks in bone, there were a couple of case studies published as well. One such study involving toolmarks in bone and cartilage shared by the author involved an axe and swords used during a homicide [34]. This case involved a victim being hit by various suspects during a large group fight. During the investigation, six swords and an axe were recovered for comparison to the toolmarks found on various parts of the victim. The authors highlighted their use of previously published methods in the preservation of the bone and cartilage to minimize the shrinkage of the toolmarks and how to prepare the bone and cartilage for casting. In their paper, they also explored different methods of creating test marks of the tools themselves in ballistics gel, tire, plastic tubing, and large candle wax bars. They noted that the candle wax bars created the best results as they were able to cast the entire surface of the axe in one casting. From their examination, they were able to identify the axe as having made the toolmarks on the knee of the victim.

In a second case study, these authors detail a case involving two katana swords and a victim with fifteen toolmarks in their skull [35]. Three of these toolmarks were cast using silicone casting material, both before and after the maceration process. The authors evaluated these two sets of casts and did not observe any considerable effect of the tool mark quality. Test marks of both katanas were then made in dental wax sheets and cast using the same silicone casting material for comparison. Using both light microscopy and an evaluation of the marks using the 3D ToolScan system, the three toolmarks were identified as having been made by one of the swords. The authors further discuss some benefits and limitations in the use of a 3D scanning computational comparison.

2.4. Toolmarks in tires

Moving away from toolmarks in bone, there are many other types of toolmark evidence that can be analyzed. Tires can be deflated by using various types of tools and may result in a toolmark found on the tire or in the defect. The authors of this paper look at various toolmarks in tire stabbings by exploring the friction marks produced from a stabbing type of tool entering the sidewall of a tire [36]. Eight different tools, including a single blade and double blade knife, pick tool and various design screwdrivers, were used in a total of 11 different tire brands. This study did not focus on the individual toolmarks produced by the tools, but only the friction marks created during the tire stabbing from the blades or shanks of the tool.

The results revealed that the friction marks corresponded to the shank dimensions and shape and not of the tip of the tool itself. The author also detailed that when the shank of the tool is larger than the tip portion, the friction marks corresponded with the shank and not the tip itself. While not statistically calculated in this paper, the author also observed that the dimensions of the friction mark were always equal to or larger than the dimensions of the shank itself. This research can aid an examiner in limiting the number of tools that may have been used to puncture a tire during a crime.

2.5. Drilling toolmarks

Another common place tool that can be found in toolmark casework deals with screws or drills. With the creation of improvised explosive devices, there may be many different toolmarks present from tools used to create the device. The author of this paper published details of a case study involving drill related toolmarks [37]. The Terrorist Explosive Device Analytical Center (TEDAC), located on the Redstone Arsenal near Huntsville, Alabama, serves as "the single interagency organization to receive, fully analyze, and exploit all terrorist improvised explosive devices, or IED's, of interest in the United States" with the mission "to directly contribute to the eradication of the IED threat."

An IED submitted to the laboratory for examination contained an explosively formed projectile liner with toolmarks believed to be produced by a drill bit and associated with the IED's assembly. Two additional IED's were submitted with the same design features as the original IED submission, and they exhibited the same type of toolmarks.

The author's search of the literature revealed only two articles that dealt with toolmarks created by drill bits. The author conducted additional research into the manufacturing of drill bits to gain a better understanding of the working surface and the marks produced by drill bits. The author's research revealed that the working surface of a drill bit produces individual characteristics.

Microscopic comparisons of the toolmarks between IED submissions revealed the toolmarks were produced by the same source tool. Therefore, the toolmarks provided a means to link the devices to one another.

In a letter to the editor, this author denotes an additional article that is available in the Journal of Forensic Science that "discusses foundational aspects of the drill bit, its design, use and the individuality of toolmarks they produce." [38].

2.6. Toolmark directionality in grinders

While identifying a specific tool as the creator of a toolmark is often important to a case, sometimes the conditions in which the toolmark was made is more important. In this case study, a worker at a chemical plant accidently cut into a pipeline containing flammable gas causing an explosion that resulted in four casualties [39]. Determining the rotational direction of the grinding wheel that cut the pipeline could aid in reconstruction of the accident by revealing the position of the worker relative to the pipeline while making the cut. The author's literature search did not reveal any relevant research in this area.

The author produced test cuts in steel samples using different grinders with known rotational directions. The test cuts were examined using a light microscope and a scanning electron microscope (SEM). Four criteria were found to correlate with the grinder's rotational direction: an accumulation of material where the grinding wheel entered the workpiece, ridges on the end of the cut where the grinding wheel left the workpiece, the orientation of the chips on the edges of the cut, and the direction of the cracks between chips and the workpiece on the ground area of the cut. Some of the features were only detected using an SEM and were not visible using a light microscope. Due to observed variability, caution is advised if only using the orientation of the chips on the edges of the cuts to determine rotational direction.

A "blind test" was prepared for the author consisting of ten cuts produced by an angle grinder in a steel sample with the direction of the cuts randomized. By applying the author's established criteria, the author correctly determined the rotational direction in all ten "blind test" cuts. The author noted that all the criteria may not be present to the same extent; however, if all criteria were observed together, the observations would lead to the correct result. When the author applied these same criteria to the cut in question, the author was able to offer an opinion on the directional rotation of the grinder that produced the cut.

2.7. Toolmarks and fire

Another aspect of toolmarks is the ability for a toolmark to remain unchanged in various conditions. This particular study investigated the ability to detect toolmarks on bone after a body has been burned [40]. They used three embalmed human cadavers as their test subjects. Using two different tools, a serrated knife and a machete, the authors simulated an attempt to dismember the body by inflicting a total of 55 cuts in the pelvis, thigh, knee, wrist, and ankle. After burning the cadavers, only 13% of the total injuries from the cutting tools were still visible. The authors also commented on their ability to distinguish the marks from sharp force trauma versus heat induced fractures.

2.8. Manufacturing and extrusion toolmarks

While many of the articles reviewed dealt with homicide or assault crimes, a few authors highlighted other areas that toolmark analysis can be utilized. One area where one wouldn't think toolmarks might be present would be in the world of drug related crimes. The authors in this paper looked at toolmarks on packaging materials used to contain drugs (Alaric et al., 2020). In this study, the authors explore the ability to identify straws manufactured from different places to each other. The study explores some of the characteristics like polarizing properties, straw dimensions and thickness, and mass. They also explored the toolmarks from the extrusion process. This portion of the study took 20 packets of straws from 10 different commercial outlets. These packets of straws all had similar polarizing patterns and could not be discriminated from each other based on that factor alone.

The authors observed similar manufacturing marks on the straws from within the individual packets themselves. They also observed that within a single straw across its length the extrusion toolmarks were similar with only minor changes. When comparing the straws of each of the 20 packets to each other (totaling 190 set comparisons), only 10 pairs possessed similar manufacturing marks. These pairs of straws that were indistinguishable from each other were all purchased from the same outlet, and 9 of the 10 were purchased on the same day. The single pair not purchased on the same day was purchased 8 days from each other.

In a second drug related paper, the authors of this study explored the ability to identify plastic bottles used to contain counterfeit drugs from manufacturing toolmarks [41]. This type of analysis would be a method of linking multiple counterfeiting cases to each other. The paper investigates the chemical compositions of the bottles, but also explores the toolmarks made from the mold. The class characteristics of the bottles were evaluated, and individual characteristics were compared once the class characteristics were confirmed to be the same.

Prior to the individual characteristic comparisons, the authors detailed the manufacturing process of the mold itself and evaluated the potential for this mold to produce individual characteristics. With the evaluation of potential individual characteristics confirmed, the comparison found that bottles with different counterfeit labels were manufactured using the same steel mold.

This last article in this section details the class characteristic variation between different molds used to produce zip ties [42]. The authors of this study looked at various parts of the zip tie for variation between brands, and within different mold numbers of the same brand. This study determined that there are some differences within the class characteristics across different brands of zip ties of the same size. The study also noted that there was negligible differences of the same brand and size across different mold numbers. Another notable finding is the mixture of mold numbers within a single bag. All bags that were selected had a variety of different mold numbers within a single bag with some even having all different mold numbers in a pack of 20 zip ties. The study also highlights a searchable and public database that has been created to document mold numbers, brand, and class characteristic measurements. While this database is in its early stage, it is still being expanded and can be a good resource for searching an evidence zip tie against.

In the last manufacturing article published, the authors of this paper looked at the rising trend of 3D printers. With 3D printing technology advancing and changing frequently, this study embarks on some fundamental comparison work of a 3D printed object back to the printer itself [43]. The authors looked at the ability to identify a 3D printed object back to the base plate of the 3D printer. As the object is being made, layer upon layer of filament material is being deposited on top of the previous layer. The study looked at the initial layer which was deposited onto the base plate. The authors found that an examiner can identify two objects that were printed from the same printer based on the marks transferred from the base plate onto the object being printed. The authors were also able to identify an object that had been printed back to the printer itself. With the increasing number of 3D printed items and 3D printer capabilities, this area of research is likely to expand in the coming years.

2.9. Case study of false toolmarks

While there may be many different types of toolmarks at a scene, sometimes determining if the mark on an object is even related to the crime may be difficult. In this case study involving a burglary, two tools, a cleaver and a hammer, were potentially used to break into a safe and were recovered at the scene [44]. The author performed the comparison of the recovered casts of toolmarks on the safe and a wardrobe back to the cleaver. This comparison was not able to eliminate or identify these marks as coming from the cleaver due to the poor quality of microscopic detail. While looking through the scene photographs, the author noticed some other potential toolmarks that could be associated with the hammer that were not collected originally. Through experimentation, examination, and research, the author was able to determine the circular toolmarks were produced by suction cups affixed to the wardrobe with glue and not from the hammer. While this did not help to solve the burglary, it shows the importance of experimentation and replication of toolmarks when analyzing a toolmark case.

2.10. Toolmarks and statistics

With a push for statistical data to accompany firearm and toolmark casework, there was a surprising void of papers that focused solely on non-firearm related toolmarks and statistics. The authors of this paper, however, did publish this article containing some interesting data related to statistical analysis in toolmarks [45]. The authors began with a thorough summary of previous research that involved statistical analysis on toolmarks as a reference point for the reader. In their study, they used three different sets of tools for their experiment: screwdrivers, bolt cutters, and cutting pliers. One notable aspect of their method was their creation of a device that secured the screwdrivers to allow consistent and repeatable angles when making the toolmarks on the lead sheets.

The statistical tests that they used to analyze the data sets are known as uniform local binary pattern feature and the random forest pattern recognition method. The results of the study exhibited accuracy rates when evaluating a source tool back to a toolmark at above 90% with most of their experimental sets, with the bolt cutter toolmarks being the lowest at above 81% accuracy.

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