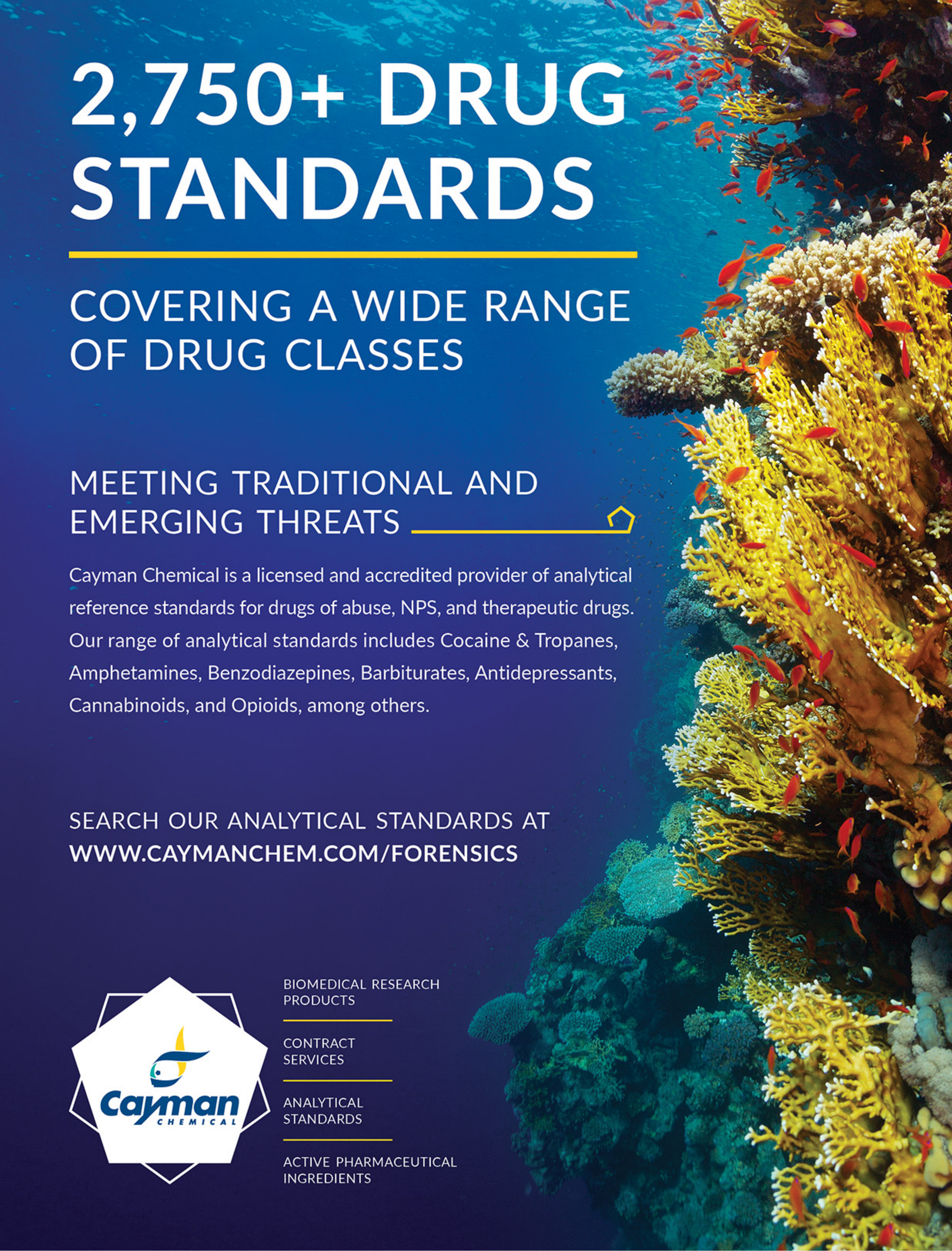
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TECHNICAL NOTE

Criminalistics

Recovery of 3D footwear impressions using a range of different techniques

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Abstract

Three-dimensional (plastic) footwear impressions are frequently found at, or in the vicinity of a crime scene, and may provide a valuable form of evidence or intelligence. This paper compares the traditional methods of casting and/or two-dimensional photography with Structure from Motion (SfM) photogrammetry. We focus both on the recovery of class characteristics (sole pattern) and randomly acquired characteristics caused by damage. We examine how different recovery techniques influence visualization of outsole features and discuss what effect this may have on evidential value. Five shoes and their associated three-dimensional impressions made in both sand and soil were compared using a grid system and tread descriptors commonly used in the UK. We conclude that within the limitations of this study SfM photogrammetry allows superior levels of visualization of both class and randomly acquired characteristics, giving a better definition in detail in some instances. The use of SfM as a complementary approach can therefore lead to a potential increase in evidential value.

KEYWORDS
footwear impression, three-dimensional, casting, evidence recovery, randomly acquired characteristics, photogrammetry

1 | INTRODUCTION

Methods for the recovery of 3D footwear impressions at crime scenes have remained relatively unchanged for decades (1,2). Impressions are either cast or simply photographed in situ. There is little or no research into the effectiveness and sources of error associated with casting despite its widespread use. Protocols for mixing the plaster are largely informed by a practitioner's field experience although Bodziak (1) provides some guidance. The research that is available such as the recent paper by Sabolich (3) focuses on the use of fixative sprays or other practical/logistical solutions such as mixing methods and containers (4). None of this work assesses the errors or accuracy of casting. A recent exception is that by Snyder (5) who compared casting and examination quality photography. She states that dental stone casts are often not collected due to costs, mainly in terms of time, and due to a belief, that photography provides a sufficient amount of information. Snyder shows that casts are superior in most cases capturing randomly acquired characteristics (RACs) that are not visible on photographs. Recently, the development and increased use of Structure from Motion (SfM) photogrammetry (2) offer an alternative method of capturing 3D impressions. SfM can digitally capture a 3D impression in contrast with a physical cast. The aim of this paper is to provide an initial comparison of the effectiveness of photography, casting, and digital 3D models in capturing class characteristics and RACs in footwear impressions.

2 | METHODOLOGY AND ANALYSIS

The aim of the first experiment was to simply compare the visibility of class characteristics across different recovery methods. Five outsole impressions using five different shoes were made in oven-dry playground sand by the senior author (weight 57 kg). The impressions were made indoors in a controlled environment (i.e., shallow plastic tray). The five shoes used were: 1. Adidas hiking shoes; 2. Adidas fashion trainers; 3. New Look trainers; 4. Nike Running trainers; and 5. Nike fashion high top trainers. They were selected as representative of a cross-section of typical outsole designs currently on the market. Three of those shoes (1. Adidas hiking shoes, 2. Nike running trainers, 3. Nike fashion high top trainers) were worn for a second time by the senior author to make impressions in a natural sand environment. The main differences between the two sand types were sorting, moisture content, and bulk density. The playground sand was well sorted with 90% of particles between 425 and 300 µm, by contrast the beach sand contained only 40% within this grain-size range. Moisture content and bulk density where both higher in the natural sand environment as one would expect.

The above experiment was then repeated replacing sand with purchased topsoil and again placed within a shallow tray in the laboratory. The senior author made all the impressions once again using the same shoes having first cleaned the outsoles. The natural soil had a higher clay content (clay loam) and bulk density than the bought topsoil (sandy loam).

The second part of this study assessed the preservation of individual damage features or randomly acquired characteristics (RACs). For this study three brand new, identical and unused shoes (Branded Air Tech, Female Sizes 4, 5, and 6) were used to make impressions The three outsoles had artificial damage features added and each shoe had an increasing level of damage severity. The artificial marks were made to replicate the normal damage shoes might experience such as wear, cuts, holes, and abrasions. These shoes are referred to as Shoe A, B, and C, with C being the most severely modified (Figure 1). Footwear impressions were made in a controlled indoor environment using oven-dry playground sand within a shallow tray. The shoe wearer simply walked through the tray to leave an impression. Fine dry sand allows for fine detail to be captured in an impression and increases the chances of RACS being transferred from sole to impression.

After all impressions described above were made, they were photographed in line with photogrammetry guidelines (7). This includes taking a minimum of 20 photographs from varying oblique angles and directly above, ensuring all photos overlap. The photographs were then uploaded to freeware DigTrace (www.digtrace.co.uk), which uses Structure from Motion (SfM) photogrammetry to create 3D point cloud models. The models where scaled and then auto-rectified so that the principal plane was orthogonal to the vertical and then color rendered using a variety of different color ramps (2).

Casts of all footwear impressions were also then made using current and advised methods as set out in the UK National Policing Improvement Agency Footwear Marks Recovery Manual (6) with small modifications in alignment with the casting material manufacturer's instructions. Precisely 1 kg of dental stone (Table 1), was measured and temporarily stored in large Ziploc bags. Each bag per footwear impression was used with 600 ml of water poured into the bags and mixed by hand for a minimum of 3 min. Once the consistency of the dental stone plaster was lump-free and resembled thick cream, a corner of the bag was cut and the mixture poured slowly onto the impression surface, starting outside of the impression and working in so as to not disrupt any of the impression during the first pour impact. Where necessary a metal dam was used to hold the plaster in place. The dental stone was then left in the impression for a minimum of 45 min. All casts were then left to air dry for a minimum of 72 h on drying racks allowing airflow around the cast, after which the casts underwent cleaning under a running tap, with a soft brush removing loose debris. The casts where photographed above in normal light using a tripod.

Highlights

- Use of SfM Photogrammetry for recovery of footwear impressions.
- SfM recovery compares favorably over other methods when visualizing RACs.
- One key advantage of SfM is the use of depth color renders.
- Digital recovery allows superior visualization, digital file sharing, and searching.

Crime scene quality photographs were also obtained from directly above each impression using a tripod following best practice set out in the UK National Policing Improvement Agency Footwear Marks Recovery Manual (6). No additional lighting or post-production modification of the photographs were however used to enhance the visibility of features. This was due to the nature of the results of oblique lighting. A light source from one direction may enhance some features and cast others into shade. This therefore requires multiple pictures to gain better visualization of the whole impression. As only one image was being used for the comparison, no additional lighting was used and all lighting conditions were therefore consistent.

The UK National Footwear Database uses a series of 14 descriptors to characterize a footwear impression and index it for future searches (Table 2). These descriptors can be used as a means of comparing the three capture methods used in this study: do all methods capture the same level of detail and therefore result in the same number of characterization codes? For each environment, four vertical photographs were aligned in Adobe Illustrator, using rigid scaling and translation to maximize the overlap. Overlap was gauged by varying the image opacity. This was repeated a minimum of ten times to ensure repeatability

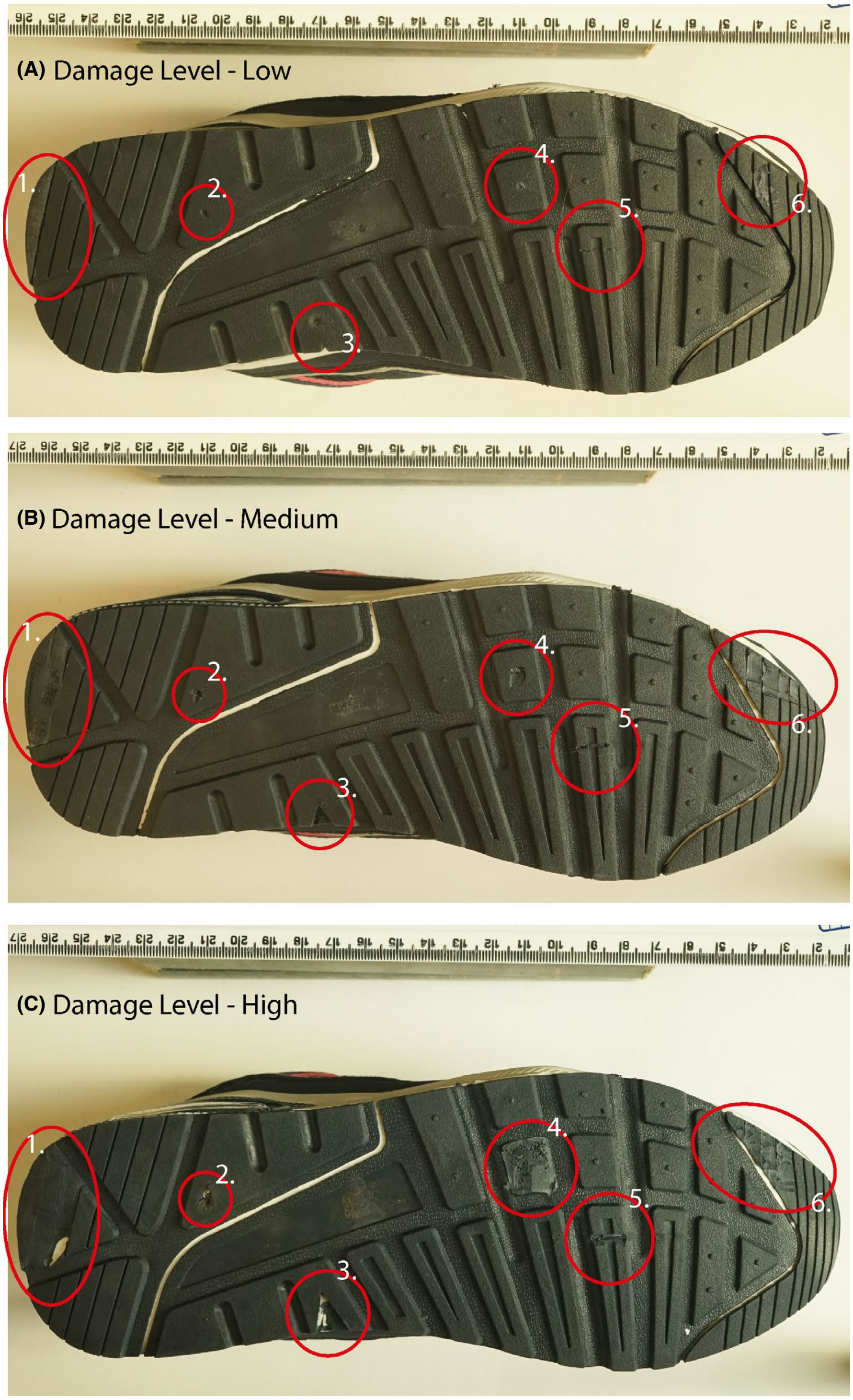

FIGURE 1 Set of shoes with artificial damage features added. (A) Lowest level of damage, 1–6 highlighting individual damage features. (B) Medium level of damage, 1–6 highlighting individual damage features. (C) Highest level of damage, 1–6 highlighting individual damage features

TABLE 1 Properties of dental stone SP used in this study

Plaster-of-Paris type (Water:powder ratio, by weight)	Relative density	Yield	Flexural strength	Compressive strength	Setting expansion	Setting time at 18°C
Dental SP (65:100)	1.35	0.75 L/kg	5 N/mm^2	25 N/mm^2	0.20%	12 min

of the alignment. A grid of 24 squares was then placed over the aligned impressions and the pattern descriptors present in each square recorded. Figure 2 shows an example of the aligned. When making an assessment of descriptors in each square the operator referred back to the original outsole, unaligned image, cast, or 3D SfM model. Because this was bespoke to each environment, the absolute number descriptors vary slightly due to subtle variation in the placement of the grid. For each recovery type, each output was coded and the total number of descriptors recorded. A single operator was used to assess both descriptors and RACs.

TABLE 2 Pattern descriptors

D01	Bar
D01-01	Wavy Bar
D01-02	Curved Wavy Bar
D02	Circular
D02-01	Target
D03	3 sided shape
D04	4 sided shape
D05	5 sided shape
D06	6 sided shape
D07	Complex shape
D08	ZigZag shape
D09	Text
D10	Logo
D11	Lattice
D12	Textured
D13	Hollow
D14	Plain

3 | RESULTS

The results from the class characteristics experiment are shown in Table 3 and a visual example of the comparison using one shoe can be seen in Figure 3. The percentage of identified descriptors varies both with environment and method. Pair-wise Mann–Whitney tests were used to explore the significance of these differences (Table 4), having first established that the distributions were not all normal (Casts $p < 0.05$; DigTrace $p > 0.05$; Photographs $p < 0.001$). According to these results, there is no significant difference at 95% between casting and photography in terms of the number of descriptors than can be recognized; however, SfM appears to provide superior recognition of descriptors compared to both casting and photography, although in the latter case this significance falls if we use a Bonferroni corrections. The advantage of SfM methods relative to conventional photography in recognizing class characteristics is marginal, especially given that the crime scene photographs could be enhanced. However, in both cases these recovery methods are superior to casting. Figure 4 illustrates the visualizing power of the depth color renders in SfM models in picking out class descriptors relative to that visible in a cast. Note how the triangular pattern is visible in the SfM model but not in the cast and better definition of some of the finer detail.

Looking beyond the class descriptors at more specific RACs we see further differences. Table 5 grades each RAC as either not identifiable, identifiable, or clearly identifiable. The heel damage is clearly identifiable in both the cast and the SfM recovery methods but is less obvious in the 2D photograph. As one would expect both 3D methods are superior at defining 3D wear the edges of which are often gradational especially at the heel.

The hole damage in the lateral middle area of the outsole is more visible in the SfM models when compared to the physical cast, or a photograph (Figure 5). The color depth render in the SfM model

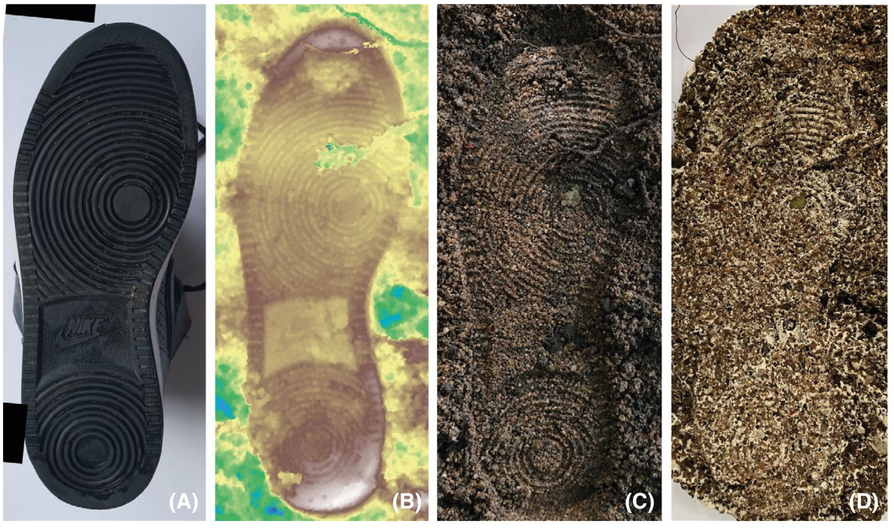

FIGURE 2 Aligned images before grid overlayed and features recorded. (A) Rectified image of Nike 2 (hightop trainer) sole. (B) 2D render from DigTrace of impression made from Nike 2. (C) 2D image of impression made from Nike 2. (D) Cast made from impression, made from Nike 2

TABLE 3 Feature counts from photograph of shoe sole, compared with feature counts from an impression cast, a photogrammetry model of an impression, and a 2D photograph of the impression

	Total features on control	Features in cast	% Similarity to control	Features in SfM model	% Similarity to Control	Features in 2D photograph	% Similarity to control
Sand control							
Adidas 1	61	31	50.82%	37	60.66%	36	59.02%
Adidas 2	30	22	73.33%	23	76.67%	21	70.00%
New look	48	10	20.83%	33	68.75%	7	14.58%
Nike 1	58	31	53.45%	47	81.03%	46	79.31%
Nike 2	40	29	72.50%	29	72.50%	27	67.50%
Sand natural							
Adidas 1	56	5	8.93%	19	33.93%	6	10.71%
Nike 1	51	0	0.00%	14	27.45%	8	15.69%
Nike 2	37	5	13.51%	23	62.16%	16	43.24%
Mud control							
Adidas 1	64	6	9.38%	12	18.75%	6	9.38%
Adidas 2	34	6	17.65%	13	38.24%	5	14.71%
New look	54	0	0%	0	0%	0	0.00%
Nike 1	58	6	10.34%	15	25.86%	1	1.72%
Nike 2	37	5	13.51%	13	35.14%	4	10.81%
Mud natural							
Adidas 1	56	10	17.86%	17	30.36%	5	8.93%
Nike 1	51	13	25.49%	20	39.22%	11	21.57%
Nike 2	37	18	48.65%	18	48.65%	12	32.43%

Note: The absolute number of control features varies between each experiment due to ensuring that optimum alignment of the images.

helps bring this out and the peak in the sand prior to casting appears to be modified by the weight of plaster. The missing triangle in a medial middle part of the outsole (Figure 1) is visualized well in both 3D recovery methods of the medium and high damage impressions. It is not clearly identified in the low-damage case when viewed via the 2D photograph and the cast. The shredded square feature in a lateral middle part of the outsole (Figure 1) consists in the low-damage version of a removed small round bump on a raised square and is subtle. This is visible in the 3D SfM model due to the color depth render and can be felt in the 3D cast but is harder to visualize in the 2D photograph, although oblique lighting might help. The medium damage version consists of a wider hole within the square and with increased depth it is clearly visible in all methods. The high-level damaged version has had the entire square sliced off and becomes more difficult to see. This area is revealed in the 3D models as an uneven area with a different texture to similar squares. The damage is visible in the 2D photograph but not as clearly visualized.

None of the methods allow for visualization of the low-level damage slit in the medial middle part of the outsole (Figure 1). This is most likely due to the feature being of such small width that it was not recorded in the original impression and therefore was not there to recover. It can be seen however in the middle-level damaged impressions, clearly in the SfM 3D model and 2D photograph but less so in the cast. For this particular feature, in order to see it on the cast, you need to be able to feel it, physically touching the cast to notice the slight dip where the cut is. The high-level damage results can be seen in all methods due to a wider cut.

The final toe damage features are not easily visualized due to the disturbance of the area upon lifting a shoe. The high-level damage can be seen however on the 3D SfM model and is the only recovery method showing the damage not just as a result of general disturbance through motion. The feature is partly visible in the high-level cast and 2D photograph but could easily be assigned to generic disturbance.

4 | DISCUSSION

The visualization of class characteristics is one of the first stages in the analysis of footwear impressions. In the UK, this is done by a series of fourteen descriptors. The results of this study show that using SfM photogrammetry and/or 2D photography gives superior recognition of class descriptors at least in the examples used here and while other operators and impressions may give different results this work hints at a potential advantage that is worth exploring further. The difference between 2D photography and SfM methods is present, but minor. The quality of the 2D photographs could be improved by oblique light and this might make the difference even smaller. However, in time-constrained

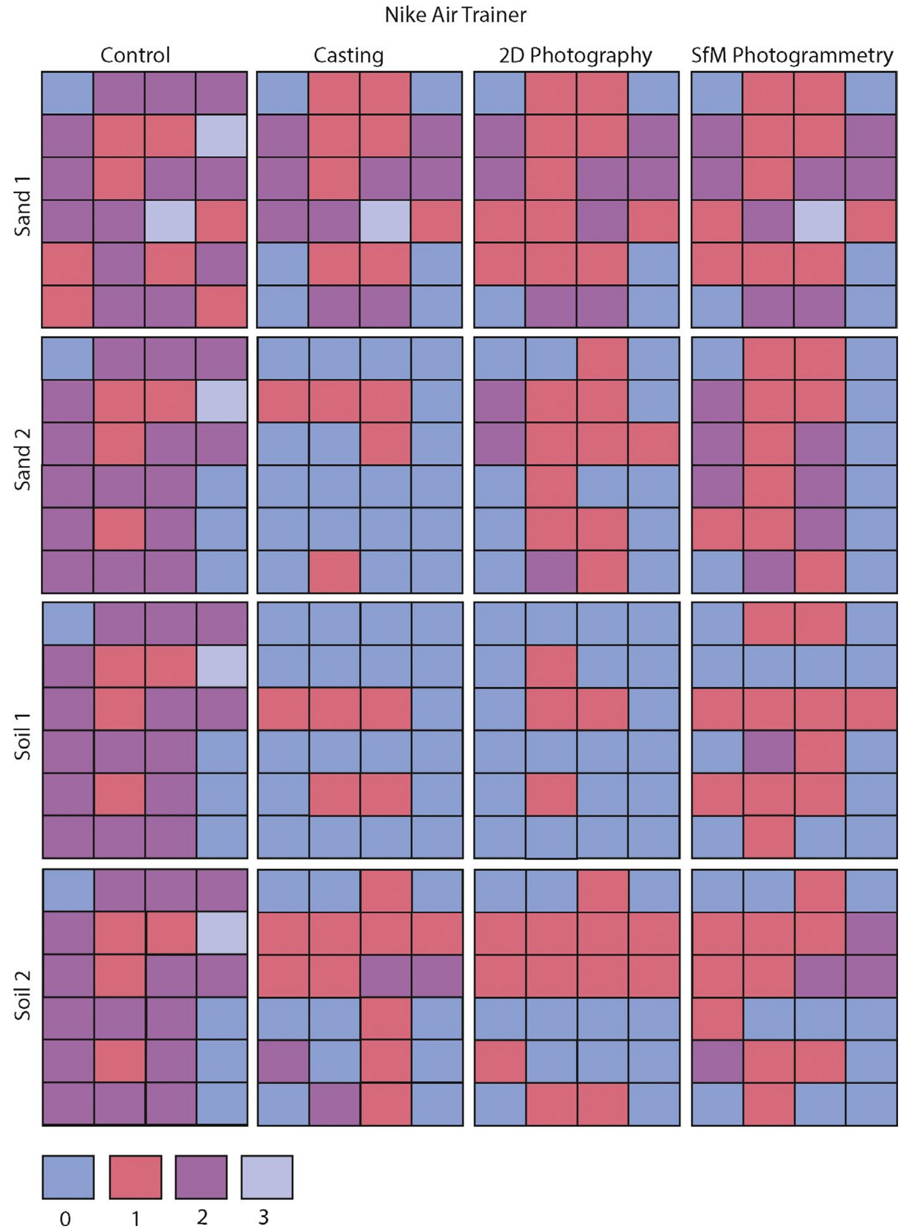

FIGURE 3 An illustration of the number of descriptors found in each cell per grid for a Nike Air Trainer. Row 1 shows a controlled sand environment, Row 2 shows a natural sand environment, Row 3 shows a controlled soil environment, and Row 4 a natural soil environment. Column 1 illustrates the results from looking directly at the shoe sole, labeled 'Control'. Columns 2, 3, and 4 refer to results from casting, SfM photogrammetry, and photography, respectively

TABLE 4 Pair-wise Mann–Whitney tests with Bonferroni corrections shown in parentheses

	Cast	SfM	Photography
Cast			
SfM	0.0161 (0.04831)		
Photography	0.9669 (1)	0.02793 (0.08378)	

circumstances where the value of a piece of evidence is not yet clear at the outset maximizing photographic recovery in this way may not be a priority or always done. In this case, a SfM model is likely to be superior in the majority of cases. It takes a matter of as little as 2 min to take the additional photographs for an SfM model and the ability to change the color depth render when analyzing the track is powerful and gives you more analytical options than a 2D photograph taken in haste at a crime scene. We are not however suggesting that 2D photographs should not be taken, just that the additional time to obtain the photographs for an SfM model is negligible and may enhance the quality of the capture evidence.

FIGURE 4 Grid Comparisons. (A), (B), and (C) refer to the same grid section on Adidas1 shoe, cast and DigTrace model. (D), (E), and (F) refer to a different grid section again on Adidas1. (G), (H), (I) refer to the same grid section on New Look shoe, cast, and DigTrace Model

In spotting subtler wear characteristics such as RACs both the 3D recovery methods give superior results to a 2D photograph, as has been stated before (1,5). Casts allow one to 'feel' textures, but are bulky, difficult to store, and can be subject to recovery failure (1). They are also not routinely, at least in the UK, undertaken except in the most serious of cases due to the cost and time involved in their recovery. The 3D SfM model allows depth color renders and digital measurements to be taken and while they cannot be 'felt' unless 3D printed there are more analytical options available. We suggest that this provides a greater range of options for visualizing RACs as shown in Table 5. The results reported here are limited by the experimental design and could usefully be replicated by other researchers

TABLE 5 Results of RAC visualization from the three recovery techniques analyzed

Damage feature	Cast – low damage	Photogrammetry – low damage	2D Photography – low damage	Cast - medium damage	Photogrammetry – medium damage	2D Photography – medium damage	Cast – high damage	Photogrammetry – high damage	2D Photography – high damage
1 – Heel damage	Not identifiable	Not identifiable	Not identifiable	Clearly identifiable	Clearly identifiable	Identifiable	Clearly identifiable	Clearly identifiable	Clearly identifiable
2 – Hole	Not identifiable	Identifiable	Not identifiable	Not identifiable	Clearly identifiable	Clearly identifiable	Clearly identifiable	Clearly identifiable	Clearly identifiable
3 – Triangle	Not identifiable	Clearly identifiable	Not identifiable	Clearly identifiable	Clearly identifiable	Clearly identifiable	Clearly identifiable	Clearly identifiable	Clearly identifiable
4 – Square damage	Not identifiable	Identifiable	Not identifiable	Clearly identifiable	Clearly identifiable	Clearly identifiable	Identifiable	Clearly identifiable	Clearly identifiable
5 – Straight cut	Not identifiable	Not identifiable	Not identifiable	Identifiable	Clearly identifiable	Clearly identifiable	Clearly identifiable	Clearly identifiable	Clearly identifiable
6 – Toe damage	Not identifiable	Identifiable	Not identifiable	Identifiable	Identifiable	Identifiable	Identifiable	Clearly identifiable	Clearly identifiable

Note: The specific RACs referred to are shown in Figure 1.

focusing on perhaps using a battery of footwear examiners to do the coding. The results are however suggestive of the potential of SfM as an additional cost-effective tool in the armory of footwear experts.

5 | CONCLUSION

This simple experiment suggests that visualizing class characteristics made by outsoles are favored by either 3D SfM photogrammetry or 2D photography. Casting and 3D SfM provide better visualization of randomly acquired characteristics where the use of touch in the case of casts and different color depth renders in visualizing 3D digital models comes into their own. Footwear practitioners, like any other professional, have established protocols by which evidence is recovered. No doubt one reading this paper would recover the evidence differently or criticize the quality of the 2D photographs used in the comparison. Further work should be undertaken to compare these methods in light of the limitations of this study, including the use of oblique lighting and considering the effect a single operator has on the results.

Our aim is not to prove that one method is better than the other but simply to raise awareness of alternative methods and approaches. Digital SfM photogrammetry produces accurate, reproducible results (7) and as shown here in certain circumstances give superior visualization of both wear and individualizing footwear characteristics.

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FIGURE 5 Left column shows vertical photographs of impressions made in sand with artificially damaged shoes (A), (B, and (C). Middle column shows a set of photographs of castings output made from left impressions. Right column shows SfM photogrammetry outputs from left hand impressions. 3D point clouds have been interpolated and rendered in 2D 'terrain'. Multiple color renders available, each bringing out different elements of detail. Shoe (A) Low-level damage output. Shoe (B) Medium level damage output. Shoe (C) High-level damage output

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