Technological innovations in the collection and analysis of three-dimensional footwear impression evidence

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Dissertation submitted in partial fulfilment of the requirements for the degree
‘Doctor of Philosophy’, awarded by Bournemouth University

2020

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Abstract

The development of digital 3D trace recovery in the fields of geology and archaeology has highlighted transferable methods that could be used for the recovery of 3D footwear impressions under the umbrella of forensic science. This project uses a portfolio of experiments and case studies to explore the veracity and application of SfM Photogrammetry (i.e., DigTrace) within forensic footwear. This portfolio-based research includes published papers integrated into conventional chapters. A method of comparing the accuracy and precision of different measurement methods is developed and introduced and gives a comparative view of multiple recovery techniques. A range of simulated crime scene and laboratory-controlled experiments have been conducted to compare different recovery methods such as casting, photography and SfM photogrammetry. These have been compared for accuracy, practicality and effectiveness. In addition, a range of common and lesser common footwear bearing substrates have been compared using SfM as well as other methods. One of the key findings shows that DigTrace SfM photogrammetry software reliably produces accurate forensic results, regardless of the camera used for initial photography and in a multitude of environments. This includes but is not limited to, soil, sand, snow, and other less obvious substrates such as food items, household items and in particular carpet. The thesis also shows that SfM photogrammetry provides a superior solution in the recovery of 'difficult to cast' footwear impressions. This finding allows for 3D recovery of impressions that would otherwise have only been photographed in 2D. More generally this project shows that 3D recovery is preferential to 2D and aids in the identification of individual characteristics and subsequent positive analysis. Overall, the thesis concludes that SfM photogrammetry is a viable and accurate solution for the recovery of 3D footwear impressions both as an alternative and replacement to 2D photography and conventional 3D casting. SfM 3D recovery provides increased visualisation of footwear evidence and individualising marks. Digital evidence obtained in this way integrates with the increasingly sophisticated search algorithms being used within the UK's National Footwear Database and allows rapid file sharing, retrieval and evidence sharing. Moreover, the technique has significant cost saving in terms of time, equipment and resources. It is the author's opinion, having consulted a wide audience of footwear examiners and crime scene employees, that this technique should, and can be, adopted quickly by forces in the UK and USA and disseminated for use.

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List of abbreviations

3D	Three Dimensional
RAC	Randomly Acquired Characteristic
UK	United Kingdom
SfM	Structure from Motion
NERC	Natural Environment Research Council
BU	Bournemouth University
2D	Two Dimensional
NFD	National Footwear Database
NFRC	National Footwear Reference Collection
PCAST	President’s Council of Advisors on Science and Technology
NRC	National Research Council
NIST	National Institute of Standards and Technology
SE	Standard Error
SD	Standard Deviation
ICP	Iterative Closest Point
RMS	Root Mean Squared
NPIA	National Policing Improvement Agency
ISO	International Organisation for Standardisation
NS	Not significant
dSLR	Digital Single Lens Reflex
CSI	Crime Scene Investigator

Acknowledgements

Thanks must first of all go to my supervisory team, Professor Matthew Bennett and Professor Marcin Budka, for their encouragement and guidance over the last three years. Their expertise and commitment have been invaluable and have expanded the project, and my own goals within, greatly. With special thanks to Matthew Bennett and Sally Reynolds for levels of support going above and beyond.

I would also like to thank all those who have gone out of their way to encourage this project and welcome this research into the forensic community. To David Kanaris, for hosting me in the Alaskan State Crime Lab and for the personal communications which have positively steered this research. To DSI Julie Henderson, for providing contacts, information and support throughout. To all colleagues at West Yorkshire Police and Scientific Services for allowing me an insight into the world in which this research is based on. Understanding the challenges faced at all levels of the evidential chain could not have been achieved without the honesty and respect shown to me during my visit. To all colleagues at Bedfordshire Police for providing invaluable feedback on the project and assisting wherever possible with the positive progression of digital recovery. To Scott Neville and Alun Mackrill from Bluestar Software for all advice, assistance and contributions and to colleagues at Foster and Freeman for generously lending me resources to assist in my research.

A big thankyou to Dr Ashleigh Wiseman and Dr Matteo Belvedere for reading and providing priceless comments on papers heading for submission. For personal communications helping with this research and for all offers of assistance with analysis quandaries. Your generosity throughout has been greatly appreciated.

A huge thankyou to my family and friends, for being the constant pillars of stability and support they always are. With special thanks to Carol Larsen for proof reading in what can only be described as an impossible last minute time frame and to Michelle Feider, who has lived every second of this experience with me, your support has meant the world.

And finally, immeasurable thanks go to my fiancé, Andrew Wood. For encouraging, sustaining, inspiring and most of all, tolerating me through my biggest challenge yet. Your unwavering support cannot be put into words and for that, I am truly grateful.

Authors Declaration

This thesis compromises only the authors own original work unless specified in the text with due acknowledgments. For each research piece with multiple authors, a breakdown of each individual’s contribution can be found underneath the respective title.

Chapter one: Introduction

A revolution in the digital collection of vertebrate fossilized tracks has led to research growth in ichnology[1]. Digital recovery is now a standard practice with accompanying validation efforts and extensive academic and practitioner-based research (e.g., Remondino et al. 2010; Belvedere et al. 2018; Bennett and Budka 2018; Falkingham et al. 2018). The transition from physical casting of impressions, through to digital scanning, and on to more user and cost-friendly photogrammetry has been adopted in many scientific communities (e.g., Charbonnier et al. 2013). This transition shows the potential future for other communities to adopt in the same way, but with the additional benefit of having a large amount of scientific research already in place. It is therefore proposed in this thesis that the forensic footwear community could benefit in this way and undertake a similar trajectory of change. The use and operational adoption of Structure from Motion (SfM) photogrammetry in the recovery of three-dimensional (3D)[2] footwear impressions is therefore proposed.

Digital 3D data within forensic science is currently a luxury (Gamage et al. 2013; Crabbe et al. 2014; Raneri 2018; Carew and Errickson 2020) afforded to those with large budgets and ample time and therefore restricted to important or so-called capital cases. The advent of affordable and digital 3D methods is increasingly a viable option for worldwide implementation. How we apply and deploy these methods for the greatest impact within the field of footwear is explored in this thesis. Navigating such an under-researched and yet valuable discipline has led to the exciting possibility of revolutionary scale change.

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[1] Ichnology is the study of trace fossils usually divided into vertebrate and invertebrate traces.

[2] Three dimensional impressions are sometimes referred to as plastic traces (Bodziak 2017)

1.1 **Aims and objectives**

The overarching aim of this research is to provide a scientific foundation for the application of SfM photogrammetry in recovering 3D footwear impressions. This includes exploring the benefits, limitations, and implications of the use of this method in both an academic and a forensic operational setting. Secondary to this is the aim of simply demonstrating the potential contribution that SfM could make to the forensic community.

There are several component questions which feed into this broad aim as set out in Table 1.

	Research Question	Chapter
1	Is the use of SfM photogrammetry as a 3D footwear impression recovery tool scientifically valid? This is defined using the President's Council of Advisors on Science and Technology (PCAST) report (2016) which discusses the key points of foundational validity to include reliability, reproducibility, repeatability, accuracy, and consistency.	3
2	Is the use of SfM photogrammetry scientifically valid in the range of environments in which 3D footwear evidence is typically found in a country such as the United Kingdom (UK)?	3
3	What are the practical advantages of SfM photogrammetry when measured against current methods and practice?	3,4
4	Do the outputs of SfM photogrammetry produce superior visualisation of impression features when assessed next to examples of current methods?	3,4
5	What is the measure of repeatability for currently used footwear recovery methods, specifically casting?	4
6	How do each of the elements of footwear analysis, class, wear and individual behave over the course of a shoe's existence?	All
7	How can areas of 3D footwear recovery that are often overlooked, have their value increased through the use of SfM?	All
8	Can the introduction of digital recovery also introduce statistical reporting that satisfies both traditionalist approaches and Bayesian approaches?	All

Table 1. Research questions explored within this thesis.

1.2 Structure of thesis

This thesis is split into five core chapters and follows an integrated thesis format in accordance with Bournemouth University (BU) regulations. It therefore contains completed research papers throughout which have either been published, submitted, or prepared for submission. Each paper is placed in the thesis at the logical point but to save repetition, a single master reference list is provided, and all figures have been re-numbered sequentially to avoid confusion. The thesis also includes short unpublished technical notes that address key questions with less emphasis on producing finished papers although this may be possible in the future.

Chapter One contains an introduction to the discipline, the research territory of the field and provides a rationale for the research. This is followed by a chapter of integrated methods, focusing primarily on methods that fall outside specific papers (note that some methods are repeated in the individual papers). Chapter Three addresses the scientific validation of SfM photogrammetry when applied to the recovery of 3D footwear impressions and consists of four research papers plus three unpublished technical notes. These papers primarily use the software DigTrace[3]. Chapter Four assesses SfM photogrammetry in comparison to traditional methods and includes two further research papers. The thesis concludes with a final chapter of discussion and conclusions drawing out the main themes of the research and recommendations for further study.

1.3 The research landscape and rationale

The current landscape of forensic footwear related research lacks volume, in comparison to other forensic disciplines. For example, a Google Scholar search on the topic ‘Forensic Footwear’ produces 8,710 articles[4]. ‘Forensic

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[3] (www.digtrace.co.uk)

[4] According to Khabsa and Giles, (2014), when Google Scholar search parameters are set at ‘any date’, 80-90% of all articles published in English are returned.

Fingerprint' sees a return of 91,800, while 'Forensic DNA' 374,000. Other search engines such as Science Direct were utilised to search for literature alongside existing literature citation lists. A broad range of search terms were used as the terminology within footwear evidence is not consistent. The modest amount of research reflects a range of things including current use and perhaps inertia on the part of practitioners. Conversations with UK practitioners indicate an ongoing decline in the use of all types of footwear evidence[5]. The discipline is caught between those that stress the importance of expert opinion (e.g., Bodziak 1999; Bodziak 2012; Bodziak 2017) and those that seek to supplement this with automated database search algorithms (e.g., De Chazal et al. 2005; Pavlou and Allinson 2006; Pavlou and Allinson 2009; PCAST 2016; Wang et al. 2019; Park and Carriquiry 2020). Innovation around recovery compared to other types of evidence has been neglected. One consequence is that footwear evidence relies on expert opinion, and there is perhaps less focus on analytical techniques which could support these traditional opinions. This has at times cast footwear evidence in a poor light and several high-profile reports in the last two decades (NRC 2009; PCAST 2016; Science and Technology Select Committee 2019) have all but demanded that the discipline move away from an over reliance on subjectivity. They have called for an increase in peer reviewed research to supply clarity on many of the opinion-based protocols alongside a request for objective automation where at all possible. To summarise, these reports broadly express concern about the lack of scientific research to underpin forensic footwear. This has driven research into pattern matching and automation of feature identification. However, it has not led to significant growth in research into the errors and technology associated with the recovery of footprints. One could suggest that the discipline has leapt towards artificial intelligence and machine learning (i.e., automated pattern matching) without considering some of the more basic opportunities for improvement. The rationale for the current research begins here. By contributing research at this level, it is hoped that the

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[5] Alaska Scientific Crime Detection Laboratory visiting Chief, David Kanaris.
CSI Training, West Yorkshire Police, visiting Iain Wilson.
West Yorkshire Police CSI shadowing 2 shifts with different CSIs.
West Yorkshire Police Identification Bureau visiting Expert Ryan Harris and colleagues.
Bedfordshire Police Scientific Services visiting Expert Sean Doyle and colleagues.

impact will filter upwards into the realms of analysis, intelligence led policing, better quality evidence to present at court, and increased confidence in evidence accuracy.

Leaders of the footwear field have a large part to play in teaching, establishing the norms of practice and in the progression of the discipline. William Bodziak, well known for his part as an expert witness in the OJ Simpson trial, has dedicated a lifetime to footwear evidence and is responsible for a large part of the existing research. The latest edition of his book (Bodziak 2017) covers a variety of aspects of footwear evidence including the recovery of 3D impressions. It does, however, only reference casting and photography as relevant methods for 3D recovery despite the widespread use of alternatives in other fields such as vertebrate ichnology. The result is that the audience is presented with the assumption that options for recovering 3D footwear impressions are limited. The use of digital 3D recovery, via laser scanning (Bennett et al. 2009), multiview stereo (Andalo et al. 2011), or SfM photogrammetry (Bennett and Budka 2018) are all methods that have been highlighted as having potential for 3D footwear recovery but are not discussed in Bodziak's (2017) book. One of the aims of this thesis is to correct this omission.

This thesis therefore aims to fill the gap in current literature regarding digital recovery of 3D footwear impressions. This has been achieved with a portfolio of work attesting to the validity, benefits, and limitations of SfM photogrammetry and its subsequent potential to modernising the recovery of footwear evidence. Following in the footsteps of the ichnology community, who have steadily moved away from dated techniques to utilise the technology of SfM photogrammetry (Bennett and Budka 2018), this work examines if a similar trajectory can occur in forensic science.

There is a long history of the use of SfM as reviewed by Smith et al. (2016) and it has been widely applied to a range of geological (ichnological), geomorphological and archaeological problems. Specific examples of such widespread use include 3D documentation of historical burial sites (Badillo et al 2020), the monitoring of shore platform erosion (Swirad et al 2019) and the monitoring of greenhouse gas emissions from forests using drone data (Mlambo et al 2017). However, there is currently little research documenting the use of SfM photogrammetry for the recovery of crime scene evidence. It has been concluded in the National Research Council (2009) report, also by Tuttle et al. (2008) and one stemming originally from the Daubert (1993) Ruling that any new technique or approach requires a body of peer-reviewed literature focused on its application and reliability before it can be accepted as a standard in jurisprudence. Before we can develop this further, we need to understand some of the basic principles of footwear analysis and determine what we know of them in a 3D context.

1.3.1 Elements of forensic footwear

The main elements involved in footwear analysis, and therefore critical for evidence recovery, consist of three broad categories of characteristics (Bodziak et al. 2012; Figure 1; Figure 2).

Class characteristics: Features associated with the design and production of a shoe (i.e., physical size, design, sole pattern).

Individual characteristics formed as a result of manufacture: Certain processes and materials create characteristics such as air bubbles (Music and Bodziak 1988) may produce a feature that is individual to either a set number of shoes, or even a singular shoe.

Individual characteristics: which reflect the life history of the shoe once it is purchased and worn. These can be further broken down by the source of the feature, such as a feature created through general wear, or through specific damage. Damage related features are often referred to as randomly acquired characteristics or RACs.

Figure 1. **A**. Brand New, unworn Nike Air Max 90 showing all patterns and features produced in manufacture, known as class characteristics. **B.** Unbranded Worn shoe with similar characteristics to a Nike Air Max 90, red square highlighting an area showing wear characteristics. **C**. Unbranded Worn shoe with similar characteristics to an Air Mac 90, red square highlighting a damage feature, this would be described as an individual, or RAC. Nike Air Max 90 and unbranded equivalent used for illustration as most common footwear type found in crime scenes in the UK (as of May 2018).

Figure 2. A visual timeline of features of footwear on the same size 9 men's unbranded trainer worn for a period of 3 months. Note the wear features appearing rapidly and large RACs appearing towards the end of the series.

These are the details that, if successfully obtained through recovery, can alter the impact of the evidence on a case because they link a pair of shoes to a trace at a scene and therefore potentially the owner/wearer to that scene. A successful recovery technique should retain all the features available in the original trace whether it be a two-dimensional (2D) mark or a 3D impression. The idea that recovery techniques might destroy evidence is not unheard of in the discipline of footwear. The NRC (2009 p. 146) note

> "The quality of impression evidence left at the scene cannot be controlled, but failures in the initial scene work used to collect, preserve, and possibly enhance the evidence will degrade the quality of the evidence eventually used for comparative analysis."

The concept of non-destructive recovery methods is therefore critical.

The initial stage of analysis is the identification of class characteristics in order to identify the make and model of a shoe, along with any peculiarities associated with the manufacture of that outsole (Bodziak 2017). Class characteristics are the features of a shoe created when the shoe is made. These include the size, shape, style, and pattern of the tread that occurs as a direct result of the shoe manufacture (Cassidy 1980). The variability included in the manufacturing process is vast, and there are only a small number of studies that highlight the manufacture process and how this affects the examination of footwear impression evidence (Jay and Grub 1985; Bodziak 1986; Keijzer 1990; Kainuma 2005; Nisida and Suemoto 2008; Bodziak 2017). These studies tend to focus on singular types of shoes, for example athletic, and a singular manufacturing process or feature such as the presence of air bubbles. The value of research in this area may, however, be limited due to the ever-evolving methods and variability in the manufacturing process. Class characteristics are a crucial part of the analysis but their value as a single source of identification is not always clear cut (Gross et al. 2013). NRC (2009 p.147) states “class characteristics are not sufficient to conclude that any one particular shoe or tire made the impression”. None of the current studies on class characteristics, the last of which was 2013 (Gross et al. 2013), dedicate research to the discussion or investigation into class characteristics at the recovery stage. Equally, no studies are available that discuss class characteristics in relation to 3D impressions; an example of an insightful investigation would be a comparison of the 2D and 3D recovery focusing on the subsequent quality and accuracy of the class characteristics.

Within the UK a National Footwear Database (NFD) and a National Footwear Reference Collection (NFRC) are used operationally by most UK Police Forces. It is the role of the footwear examiner to input class and individual characteristic data into these systems for either intelligence or evidential purposes. These systems work using an agreed coding system that identifies class characteristics (Figure 3; Table 2). This coding system has been used within this thesis with the permission of NFD creators Bluestar Software Ltd. Whether using coded footwear or direct pattern matching, automated search algorithms lie at the heart of such databases. There is a lot of research in this field and some of the key papers include De Chazal (2005), Zhang et al. (2005), Pavlou and Allinson (2009) and Tang et al. (2010), although these examples and all other research into pattern matching use only 2D input data. The results of these studies are often discussed in terms of percentage success and one could argue that a human would still be required to check the results and the process may never be completely automated. This is one of the largest areas of research within footwear evidence with a consistent flow of work over the past two decades (NIST 2017). Once again, as is often the case with footwear evidence, the research is rarely translated into practice, although this is slowly changing (e.g., Henderson and Armitage 2018).

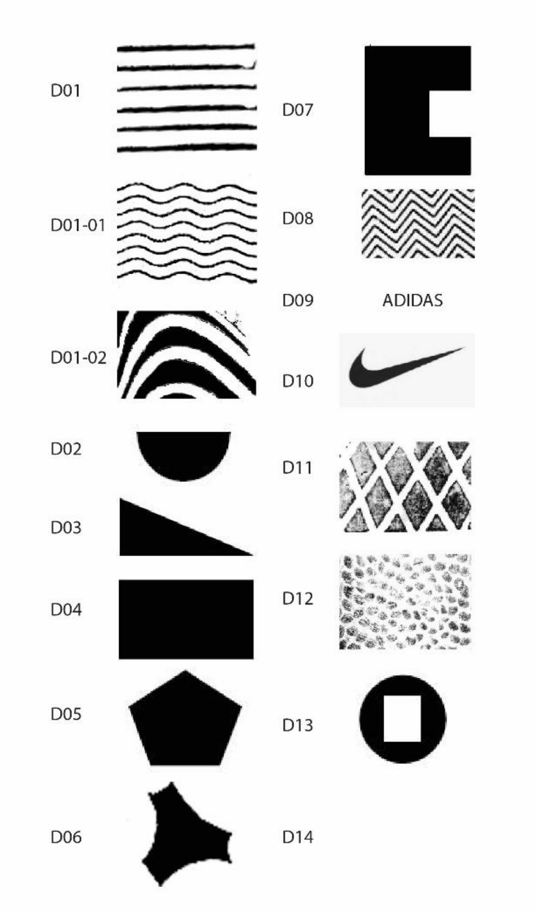

Figure 3. Examples of pattern descriptors as used in the United Kingdom NFRC

Code	Name	Description
D01	Bar	A bar of any type such as straight, angled, curved, including chevrons
D01-01	Wavy	A bar element with more than one directional change
D01-02	Curved Wavy	Any bar shape or continuous bar element that deviates from a straight line with a single rounded directional change however small the angle of the curved section
D02	Circular	Includes circle, semi-circle, oval, semi-oval, concentric circles, target, tear-drop, stud, crescent
D02-01	Target	Any concentric circle arrangement whether the centre-most circle is hollow or solid
D03	3 Sided	All types of triangle including those with one rounded side such as a pie-segment
D04	4 Sided	Square, rectangle, oblong, parallelogram, rhombus, diamond, arrowhead
D05	5 Sided	Usually a regular shaped pentagon, but includes all five-sided shapes
D06	6 Sided	Usually a regular shaped hexagon, but includes all six-sided shapes
D07	Complex	This includes shapes such as a star, arrow, waisted bar, heart and cross, and any other shape with more than six sides, such as an octagon
D08	Zigzag	A broken or continuous line that changes direction repeatedly with abrupt right and left turns
D09	Text	Any alpha-numeric characters. May overlap with D10
D10	Logo	A brand or trademark incorporating a device such as a symbol, badge, emblem, or picture. May overlap with D09
D11	Lattice	A regular, interlocking and/repeated pattern, also called a network, web or trellis, includes patterns known as brickwork, herring-bone, honeycomb, chicken wire
D12	Textured	This includes pre-dominant stippling, crepe or random patterns added by the manufacturer as part of their design.
D13	Hollow	A pattern that has the appearance of a hollow shape, such as a doughnut or frame
D14	Plain	A plain surface with no patterns or texture

Table 2. Pattern Descriptors used in the United Kingdom NFRC.

Beyond class characteristics is the assessment of wear on the outsole of a shoe and the correlation of any wear characteristics in a print or impression. Wear characteristics can be described in several ways; general wear and tear or as the gradual erosion of the shoes outsole material that occurs during contact with the substrate (Bodziak et al. 2012). Wear characteristics may also be affected by an individual's gait. Forensic gait analysis is now relatively common, that is the identification of a suspect by their gait (e.g., Birch et al. 2015; Macoveciuc et al. 2019; van Mastrigt et al. 2018; Seckiner et al. 2019). Kennedy et al. (2005) of the Royal Canadian Mounted Police suggested a high level of individualisation in the shape and size of human feet. If gait and foot shape/size are individualising it is not surprising that plantar pressure should also be distinctive, a point demonstrated by Pataky et al. (2012). Differences in limb dimensions, arm and torso movement during gait, as well as small-scale variation in foot size/shape are responsible for these pressure differences, which in turn could lead to variations in the amount and location of wear on the outsole of a shoe (Bennett and Budka 2018). The individuality of wear is, however, a relatively under-researched area, although beyond the scope of this thesis. An obvious aid to such research would be the ability to quantify the degree of wear at a specific location on an outsole, such as on the heel. The use of digital 3D recovery provides depth data that would help with this research while also aiding practitioners in comparative analysis.

The variability involved in wear makes it an ideal research area in which practitioners would benefit from large databases of wear examples. As with all other features used during analysis, determining their use and uniqueness is important in evaluating evidence, but perhaps more fundamental is to determine the best way to recover that evidence to gain the most from it. Research on wear characteristics is largely centred on analysis or formation (LeMay 2013). Whilst this is relevant and necessary there is once again no research investigating the effect recovery has on wear characteristic analysis or more specifically research relating to wear characteristics recovered from 2D compared with 3D impressions. A need for research in this area is heightened due to the issue of time elapsing between when a print or impression is made and when a shoe of interest is seized during an investigation. This gap in time leaves room for potential changes in wear and a huge number of variables will determine the extent of this wear. A question beyond the scope of this research remains, as to if a shoe can be successfully matched with a crime scene trace when it no longer shows the same degree of wear.

Identifying individual or RACs is the final step in analysis for a footwear examiner. Often referred to as individualising characteristics, it is these features that determine how unique the outsole of a shoe is and therefore, how confidently an examiner can be in confirming a particular shoe made a particular trace or impression. A review of footwear literature indicates there is more research dedicated to this type of feature than others. However, despite research efforts to support the scientific validity of RAC analysis, a 2016 US report (PCAST 2016) stated that there were, at that time, no appropriate studies supporting the foundational validity of specific identifying marks being used to associate a shoe mark with a shoe.

The NRC report (2009) also commented on the lack of consensus regarding how many RACs it takes to make a positive identification, suggesting that the discipline is open to bias in experience-based judgements. Despite researchers having responded with several quantitative empirical studies (e.g., Petraco et al. 2010; Yekutieli et al. 2012; Wang et al. 2019; Wiesner et al. 2020), this particular point has not been fully resolved. Over a decade since the NRC (2009) report was published, footwear examiners around the world still have not used a standardised process for what appears to be one of the largest concerns from a government perspective.

The formation and acquisition of RACs has been studied by Toso and Girod (1997) while others have undertaken longitudinal studies (Sheets et al. 2013), and there is also extensive work exploring the unique nature of the marks and the chance association of their occurrence (Wilson 2012; Yekutieli 2012). It is of note that there is little insight available into how RACs exist within 3D impressions. A search of eight randomly selected peer reviewed articles on RACs were examined for the type of input data used. The eight articles were taken from NISTs (2017) list of foundational studies of which there are 27 relating to the reliability and examination of wear and RACs. All eight (Stone 2006; Adair et al. 2007; Petraco et al. 2010; Hamburg and Banks 2010; Wilson 2012; Sheets et al. 2013; Speir et al. 2016; Richetelli et al. 2017) relied upon 2D data, such as those acquired by a flatbed scanner, digitalised gel prints or scanning of prints on paper. Similar research efforts using 3D data would be very insightful as it is plausible, due to the data acquired in the third dimension, especially the depth, that RACs may be easier to identify, measure, or critically, to compare. However, whilst the recovery method for the collection of such data remains as lengthy and costly as it is, it seems unlikely that this avenue will be explored for quantitative research.

A further element of RACs that has been explored, where little other work currently exists, is the examination of test impressions and their relationship with RACs. Shor et al. (2018) delivers a compelling argument for the variation that can exist in repeated test impressions, going on to describe this as an area in need of statistical analysis to fully understand. Further testing of the same nature would no doubt be beneficial for 3D test impressions.

Upon analysing footwear evidence, the absence of RACs may simply be due to poor recovery, especially in the under researched areas of 3D traces. It is likely that some characteristics simply were not recovered due to the recovery medium, the recovery technique, or beyond that, to the transport and storage of the recovered item. Therefore, the introduction of a new technique, one that may increase the ability to recover characteristics, is one that deserves an equal amount of research attention.

1.3.2 Footwear evidence in the third dimension

Research into footwear evidence which solely focuses on 3D recovery or analysis is scarce. That said, we are now beginning to see the transition from century old techniques into research that aligns with the technology available (Figure 4). As with many disciplines, the research that has been undertaken is divided into two halves. One half looks to improve the existing method whilst the other half tries to introduce new methods. It is noteworthy that one of the highest cited papers amongst footwear impression research (48 citations compared to 0-25 for most[6]) is an investigation of recovery in the three dimensions of snow impressions (Buck et al. 2007), a study introducing high resolution optical surface scanning. This study showcases the advantages of using digital capture but lacks the practical assessment of viability in respect to cost and operational deployment. Studies of casting, the traditional method of recovery for a 3D impression, include work investigating the use of fixatives to increase quality of recovered 3D impressions (Battiest et al. 2016; Sabolich 2018). There is, overall, a notable lack of research relating to casting and nothing on potential errors, tests of accuracy or any attempts to produce large datasets to study (Battiest et al. 2016). Curiously, the casting of tool mark impression evidence has studies of a more analytical nature. For example, Wang (2016) evaluates two casting materials for the use of tool mark evidence focusing on the dimensional accuracies of the results as well as sharpness, ease of use and overall quality. His research (Wang 2016), using tool mark experts to assess cast data also considers storage issues and application methods, this kind of study would fit well into the gap that currently exists in footwear casting research.

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[6] Results obtained via Publish or Perish in November 2020 - https://harzing.com/resources/publish-or-perish

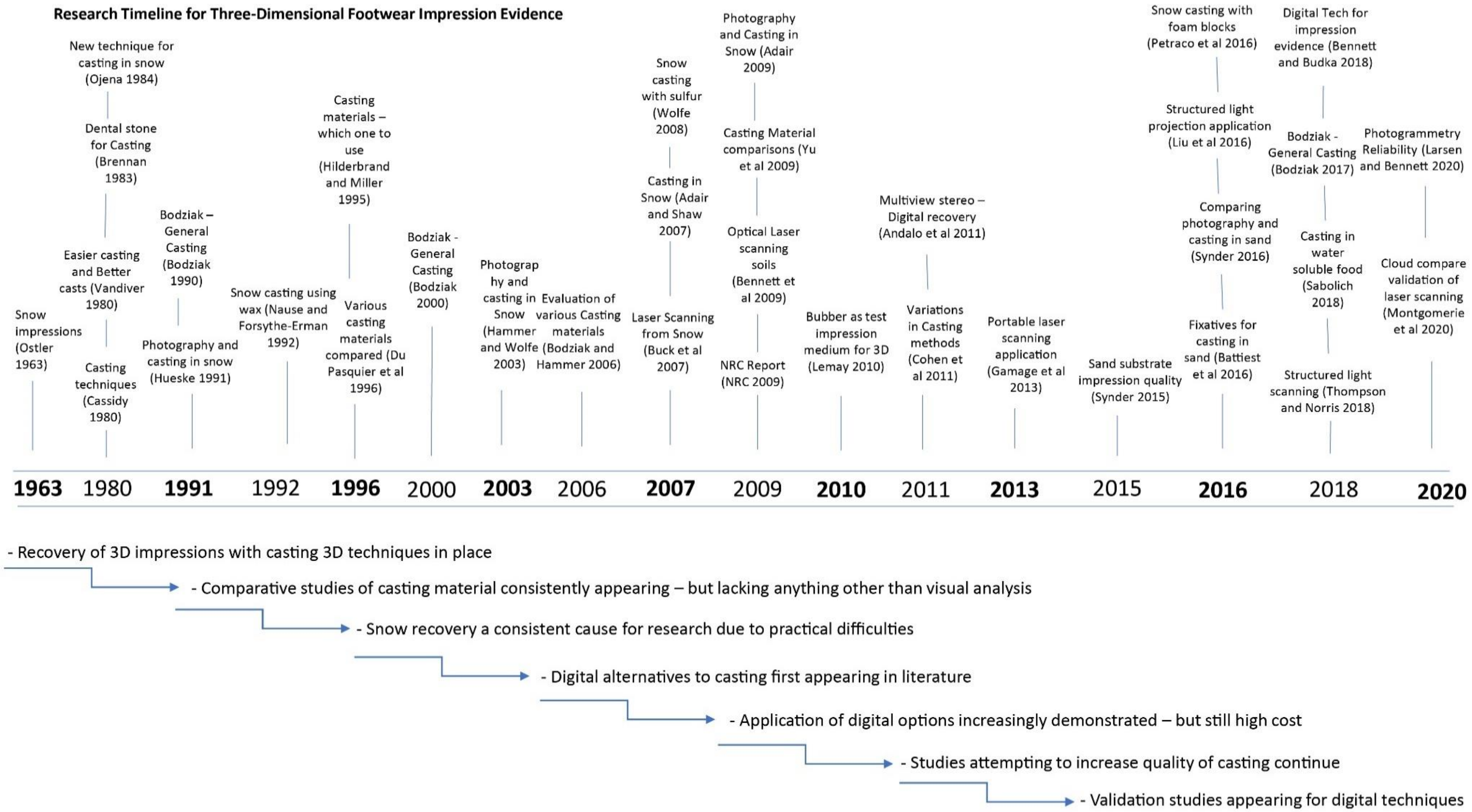

Figure 4. A timeline showing the trajectory of 3D footwear evidence research.

1.3.3 Knowledge transfer of 3D recovery

Digital 3D recovery methods are rapidly replacing more traditional techniques in many disciplines. One technique that has come to light, as an effective tool for the recovery of impression data, is close-up SfM photogrammetry[7]. There is a large body of research on photogrammetry techniques in the recovery of fossilised footprints demonstrating that it provides a reliable, low-cost solution with results equivalent to optical laser scanning (Westoby et al. 2012; Bennett et al. 2013; Falkingham et al. 2018; Bennett and Budka 2018; Bennett et al. 2020; Altamura et al. 2020). This research supports the notion that photogrammetric methods are inexpensive and can be used effectively by individuals who do not necessarily have to be experts (Bryan and Chandler 2008; McCarthy 2014). Key advantages such as the use of the method in remote areas (Westoby et al. 2012) all encourage photogrammetry to be used across a huge range of disciplines. As a result of the successful use of photogrammetry techniques to recover modern and fossil ichnological data, a bespoke programme was created by staff at Bournemouth University (BU) with Natural Environment Research Council (NERC) funding for recording and analysing 3D footwear impressions such as those left at crime scenes. It has been used throughout this thesis, although not exclusively, to illustrate the method of SfM photogrammetry when applied to the recovery of 3D forensic footwear data.

Digital recovery of fossilised tracks and more so the development of advanced analytical and statistical tools using that data, has increased community awareness of vertebrate traces and this is reflected in a huge increase in publications of fossil tracksites. Graphic representation of publications in this field (Figure 5) illustrates the frequency in which research in this area has increased since the 3D digital revolution. This is shown alongside forensic footwear research highlighting a similar increase but with significantly less volume. The quiet revolution in fossil track research has proceeded via the

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[7] SfM is used in many fields for large scale visualisation of terrain, buildings, or monuments: this contrasts with small-scale, or close-up SfM where the extent of a model is measured in a few centimetres rather than tens of metres.

provision of digital recovery tools, to the need for analytical/statistical tools for hypothesis testing based on that digital data, to an enhanced and growing community wide awareness of the value of such evidence in reconstructing the past. Forensic footwear can benefit from a similar trajectory especially since it is widely acknowledged as one of the most ubiquitous types of trace evidence left at a scene (Baiker-Sørensen et al. 2020). This is a progression that, if translated to forensic footwear, could have a huge benefit for intelligence-based policing. Beyond the standard comparison procedure which looks to confirm a shoe made a particular mark, behavioural analysis could lead investigators to a new understanding of the events, based on direction of movement, gait analysis, and beyond.

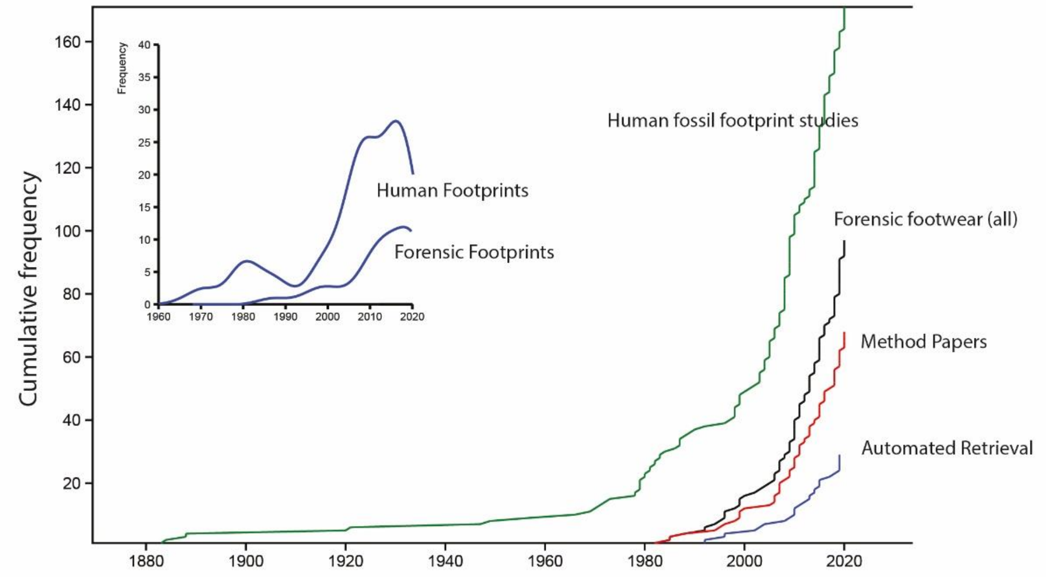

Figure 5. Timeline of increasing research in the field of ichnology separated by discipline. Cumulative frequency equals total peer reviewed research articles. Data sourced based on Google Search enabled via the software Publish and Perish, 2020[8].

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[8] https://harzing.com/resources/publish-or-perish

The translation of techniques from one discipline to another is of obvious benefit. We can also see beyond that into interesting parallels between disciplines. Fossil footprints, both animal and human, have previously been overlooked at international archaeological sites by teams prioritising the recovery of bones and stone tools. An example of which can be found at an Ethiopian site described by Altamura et al. (2018). Here potential footprint bearing surfaces were destroyed by past excavations focused on bones and stone tools. Recent test pits in adjacent areas have shown how destroyed surfaces contain hominin and other animal footprints giving important behavioural information. This has occurred in much the same way we see footwear evidence overlooked for the ‘gold standard’ evidence types such as DNA or fingerprints (Baiker-Sørensen et al. 2020). Additionally, the concept of footprints being overprinted to the point of lost data strikes a similarity between footwear impressions being overprinted by police officers and emergency responders, to the point of lost evidence. Bennett et al. (2016) used digital techniques to recover lost/hidden tracks from the famous Laetoli footprint site.

The advent of 3D technology within ichnology has progressed the discipline of vertebrate tracking from a descriptive to quantitative science. Forensic footwear recovery and analysis are potentially a whole 5-10 years behind in comparison. The below timeline (Table 3) illustrates, with key research, the progression of methodologies, equipment, and analysis techniques over the years. A shift from descriptive analysis to more analytical approaches such as Geometric Morphometrics (GMM) has taken place in the lead up to the research detailed below. Table 4 details the occurrence of footprint impression data globally that the advent of 3D digital technology has assisted in the recovery of.

Year	Research Titles	Progression Notes
2006	New interpretation of Laetoli footprints using an experimental approach and procrustes analysis: preliminary results. (Berge et al. 2006)	Berge et al. (2006) pioneered the application of geometric morphometrics (GMM) to the analysis of human tracks
2006	The application of Light detection and Radar (LIDAR) imaging Vertebrate Ichnology and Geoconservation (Bates 2006)	Use of LIDAR
2009	Integrated Lidar & Photogrammetric documentation of the Red Gulch Dinosaur Tracksite (Bates et al. 2009)	LIDAR and Photogrammetry utilised for dinosaur tracks
2009	Early hominin foot morphology is based on 1.5-million-year-old footprints from Ileret. (Bennett et al. 2009)	GMM (Geometric Morphometrics) approach adopted from Berge et al. (2006) and refined
2011	Human-like external function of the foot, and fully upright gait, confirmed in the 3.66-million-year-old Laetoli hominin footprints by topographic statistics, experimental footprint-formation and computer simulation. (Crompton et al. 2012)	Statistical comparison increasingly commonplace
2014	Human footprints: fossilised locomotion? (Bennett and Morse 2014)	Methods of digital data capture explored
2018	Digital technology for forensic footwear analysis and Vertebrate Ichnology. (Bennett and Budka 2018)	Use of photogrammetry being translated across disciplines

Table 3. The advent of 3D technology and the revolution of vertebrate ichnology.

Year	Discovery
2016	Masao et al. (2016) additional footprints at the 3.66-million-year-old footprint site at Laetoli in northern Tanzania first reported in 1979 by Leakey and Hey (Leakey and Hay 1979). A late Pleistocene site on the shores of Lake Natron was reported with hundreds of visible tracks (Balashova et al. 2016; Liutkus-Pierce et al. 2016).
2017	Gierlinski et al. (2017) describe fossil footprints dating to 5.7 Ma from Crete. Citton et al. (2017) provide an analysis of human footprints from the Grotto della Basura in Italy.
2018	In 2018 the publication of children's footprints in association with butchered hippo carcasses was reported from Ethiopia (Altamura et al. 2018). Human tracks in association with giant ground sloth in North America where described by Bustos et al. (2018). Footprints preserved in peat have been found on the Pacific Coast of Canada were described by McLaren et al. (2018). A new footprint site in South Africa is reported by Helm et al. (2018) and there has been a significant number of additional publications on this site. Belvedere et al. (2018) report on the importance of using average tracks from trackways in the analysis of human and other footprints. Urban et al. (2018) show how geophysics (magnetometry) can be used to image buried footprints.
2019	Duveau et al. (2019) reported coastal footprints of Neanderthals from Le Rozel in Normandy. In a succession of papers Helm et al. (2019a,b,c,d) continued to report footprint discoveries in South Africa. Further details on the Basura Cave footprints were published by Romano et al. (2019). Urban et al. (2019) demonstrate how GPR can be used to image buried footprints.
2020	Helm et al. (2020a,b) published more details on the South African footprint discovery. Stewart et al. (2020) reported footprints in the Arabian Peninsula. Bennett et al. (2020) reported the longest human trackway in the world from White Sands, New Mexico. Wiseman et al. (2020b) provided a definitive assessment of the Happisburgh footprints in the UK. Hatala et al. (2020) reported further analysis of the Engare Sero footprint from Tanzania. Altamura et al. (2020) reported further footprints from Ethiopia in the Middle Awash Valley.

Table 4. A selection of major footprint discoveries in the last four years showing the growing number of discoveries due to increased awareness and availability of not only 3D recovery tools, but also associated analytical tools. (Bennett and Budka 2018)

1.3.4 Justification for the research

There is an argument, not documented well in the literature, but touched upon by Bodziak (2017), that footwear evidence is often not aggressively searched for. Baiker-Sørensen et al. (2020) going as far as to say that despite its frequent occurrence, shoe marks are often neglected. This is often to do with an assumption that first responders will have destroyed or overtrodden any perpetrators print or impressions. Books such as D Hilderbrand's, *Footwear, the Missed Evidence* (2013) give further weight to the argument that, generally, footwear evidence is undervalued or misunderstood. This has been attributed to a handful of reasons but notably there is a lack of training in the collection and preservation of this evidence type. This gives us reason to assume that 3D evidence is even less likely to be searched for than 2D, as its recovery presents more of a challenge. Tables 5, 6 and 7 compile cases, described in the media, personally communicated from relevant members of the forensic community, or within scientific literature, that illustrate the existence of 3D footwear impressions and its weight in specific cases. The contents of tables 5-7 have been gathered through personal communications and in-depth literature and media searches. Multiple search terms in search engines such as google scholar and science direct were used. Thorough searches were undertaken to locate the most relevant cases/articles within archived newspapers databases and court records. Included in Tables 5, 6 and 7 are the expected mediums footwear impressions are found in such as mud and snow, but also the unexpected, from dog faeces to food items. The message being, if you look hard enough, they might exist in places no one thought to look, and potentially yielding valuable intelligence and evidential material. Some may have sat there for hours, days or months, but the potential information and insights stored in them, depending on the environment and external factors, remain.

Substrate	Example	Source
Snow	Snow - David Kanaris	Pers Communication
	Snow footprints – burglaries: UK - https://www.ibtimes.com/8-robbers-arrested-after-leaving-snowy-footprints-behind-two-different-uk-crimes-1158787	Online Media

Footprints in snow: Massachussetts - https://www.bostonglobe.com/metro/2014/01/22/woman-faces-charges-after-police-track-her-footprints-through-snow/JVUb0vDvHZsig1kxGC522O/story.html	Online Media
HADLEY v. GROOSE- Snow footprints	Case search
GUILMETTE v. HOWES – Snow footprints	Case search
Shoe and tire impressions in snow: photography and casting	Peer reviewed article
3D documentation of footwear impressions and tyre tracks in snow with high resolution optical surface scanning	Peer reviewed article
Casting of 3-dimensional footwear prints in snow with foam blocks.	Peer reviewed article
Adair T (2009) Capturing Snow Impressions	Peer reviewed article
The Dry-Casting Method: A Reintroduction to a Simple Method for Casting Snow Impressions	Peer reviewed article
https://www.msn.com/en-gb/sport/premier-league/footprints-in-snow-lead-police-to-burglary-suspect/vi-BBoxBXD	Online Media
https://www.ajc.com/news/snowy-footprints-lead-cops-burglary-suspect-atlanta/rT84TjHmdjtGONhifkqkkN/	Online Media
https://www.breakingnews.ie/world/police-use-footprints-in-snow-to-catch-burglary-suspect-618021.html	Online Media
https://patch.com/wisconsin/waukesha/footprints-snow-led-waukesha-police-car-burglars-report https://www.independent.co.uk/news/uk/crime/thieves-arrested-snow-footprints-weather-latest-a8233786.html	Online Media
https://www.msn.com/en-gb/sport/premier-league/footprints-in-snow-lead-police-to-burglary-suspect/vi-BBoxBXD	Online Media
https://keprtv.com/news/local/fresh-snow-footprints-in-pasco-lead-officers-to-burglary-suspect	Online Media
https://www.edp24.co.uk/news/crime/beast-of-the-east-helps-norfolk-police-catch-two-burglars-1-5419118	Online Media
https://www.derbytelegraph.co.uk/news/derby-news/dean-neal-burglary-chaddesden-snow-1579410	Online Media
http://newstalkkgvo.com/footprints-in-snow-help-missoula-police-nab-marijuana-burglary-suspect/	Online Media
https://www.kivitv.com/news/footprints-lead-officers-to-boise-burglary-suspect	Online Media
https://kobi5.com/news/crime-news/footprints-snow-lead-police-burglary-suspect-72391/	Online Media
https://www.nbcchicago.com/news/local/footprints-in-snow-lead-cops-K-9-to-teen-burglary-suspect-in-montgomery-473198863.html	Online Media
http://www.fox32chicago.com/news/crime/footprints-in-snow-lead-police-to-beecher-burglary-suspects	Online Media
https://www.coventrytelegraph.net/news/coventry-news/police-arrest-coventry-burglary-suspects-3029507	Online Media
(Cassidy 1980)	Book

Table 5. A selection of cases in which footwear evidence has featured in snow, surfaced via a Google search.

Substrate	Example	Source
Soil/Mud	Muddy imprint left by a Flip Flop: Atlanta https://www.ajc.com/news/crime--law/man-gets-life-after-police-connect-shell-casing-footprint-murder/c5EoOMlOKxhJuua1c3IG5K/	Online Media
	Muddy footprint with body – shoes identified in crime scene video but never seized :Massachusetts https://edition.cnn.com/2015/02/20/us/hernandez-evidence-shoes/index.html	Online Media
	Muddy shoe print: https://herald-review.com/news/local/muddy-shoe-print-leads-to-arrest-in-marijuana-case/article_19eca024-4ccd-53d9-b9ca-e2cf108aaf70.html	Online Media
	Tire + Shoe article. Casting in dirt. - http://www.crimescenejournal.com/content.php?id=0006	Online Media
	UNITED STATES v. DURAN OROZCO – Mud Footprints	Case search
	Preservation and analysis of three-dimensional footwear evidence in soils: the application of optical laser scanning. In Criminal and Environmental Soil Forensics	Peer reviewed article
	http://www.wfmz.com/news/lehigh-valley/authorities-allege-muddy-footprints-tie-suspect-to-burglary/803264312#	Online Media
	https://bangordailynews.com/2011/07/19/news/piscataquis/footprints-lead-to-brownville-burglary-suspect/	Online Media
	https://www.sthelensstar.co.uk/news/15797933.burglars-left-muddy-footprints-on-babys-cot-during-burglary-at-nursery/	Online Media
	(Cassidy 1980)	Book

Table 6. A selection of cases in which footwear evidence has featured in soil/mud, surfaced via a Google search.

Substrate	Example	Source
Sand	The Ability of Footwear to Produce Impressions of Good Detail in Sandy Soil Substrates	Peer reviewed article
	Experimentally generated footprints in sand: Analysis and consequences for the interpretation of fossil and forensic footprints.	Peer reviewed article
	(Cassidy 1980)	Book
	Sand – David Kanaris.	Pers Comm
	A Comparison of Hydrophobic Barriers for Casting Footwear Impressions in Water-Soluble Food Products	Peer reviewed article
	A Comparison of Various Fixatives for Casting Footwear Impressions in Sand at Crime Scenes	Peer reviewed article
Food Items	https://www.irishtimes.com/news/offbeat/burglar-steps-in-flour-footprints-lead-police-to-his-front-door-1.2562145	Online Media
	https://www.itv.com/news/westcountry/2016-03-04/burglar-jailed-after-leaving-trail-of-footprints-to-own-door/	Online Media
	Flour (Cassidy 1980)	Book
	Sugar (Cassidy 1980)	Book
	Birthday Cake – Roger Blackmore	Pers Comm
	Shoeprints in Turmeric – CSI West Yorkshire Police	Pers Comm
	Shoeprints in Ice Cream - CSI West Yorkshire Police	Pers Comm
	Shoeprints in curry powder - CSI West Yorkshire Police	Pers Comm
Other	Shoeprint found on forehead: Salford - https://www.dailymail.co.uk/news/article-1130469/CSI-Salford-How-footprint-embedded-mans-head-helping-police-track-attacker.html	Online Media
	Shoeprint found on forehead: Las Vegas - https://lasvegassun.com/news/2010/feb/01/forehead-shoeprint-leads-felons-arrest-office-buil/	Online Media
	Dog poo shoeprint: used DNA to link - http://www.petsville.ie/how-your-pets-can-help-solve-crimes	Online Media
	Unsolved Case with outdoor footprint evidence - https://www.express.co.uk/news/uk/82066/Plea-for-help-in-1979-murder-case	Online Media
	Bathroom Mat Shoeprints - https://www.vanityfair.com/news/2007/05/strangler200705	Online Media
	STATE v. CAMPBELL – Admissibility of footwear identification evidence	Online Media
	https://www.manchestereveningnews.co.uk/news/greater-manchester-news/swinton-vape-shop-burglars-police-15550706 - (Police not interested in footprint story)	Online Media
	https://www.heraldnet.com/news/burglary-suspect-given-away-by-oily-footprints/ - OIL Footprints	Online Media
	https://www.yorkpress.co.uk/news/10097216.trail-of-footprints-led-to-young-burglars/ - no medium described	Online Media
	Dust (Cassidy 1980)	Book
	Fire Extinguisher Propellant (Cassidy 1980)	Book
	Safe Insulation - (Bodziak 2000)	Book

Carpet – Roger Blackmore	Pers Comm
Footprints in washing powder – CSI West Yorkshire Police	Pers Comm
Footprints in Fire extinguisher propellant – CSI West Yorkshire Police	Pers Comm
Dog muck – David Kanaris.	Pers Comm
Carpet – David Kanaris.	Pers Comm

Table 7. Substrates which featured in real cases surfaced via a Google search or by personal discussion with footprint experts during secondments and during meetings.

The value of evidence is often determined by perception alone. Figure 6 examines the value, categorised by both evidential and intelligence. If every expert in a specific field attended a crime scene, every evidence type would be prioritised. As this is rarely the case, the decision making of evidence value and prioritisation is often placed upon the attending crime scene examiners. They decide if something is of evidential or intelligence value and collect it accordingly. Research on professional judgment and decision making allows an insight into the difficulties faced by crime scene examiners. Ill-defined and competing goals, conditions of uncertainty and time pressured decision making are but a few of the challenges faced (Martindale et al. 2017). Every crime scene is different and a level of improvisation in how the scene is approached is required by examiners. Martindale et al. (2017) discusses in his research the cognitive element of improvising at a scene and note for a less experienced examiner a temptation to go for a ‘quick fix’ catch up, potentially compromising the scene. The ‘quick fix’ frame of mind is attributed to the time pressure faced. A particularly relevant point raised is the temptation to bypass certain aspects to get to aspects that would yield quicker results. This is increasingly relevant to the recovery of 3D footwear impressions as time pressures are ever increasing (Unison 2015) and this is simply due to the recovery of impressions via casting remaining labour intensive and time consuming. An examiner may see an impression and choose not to recover it. Or they may not look for the impressions in as much detail as they would a ‘higher value’ piece of evidence such as fingerprints or DNA (Baiker-Sørensen et al. 2020).

Decades have passed with an air of confusion over the value of collecting 3D data from a footwear impression (Bodziak 2017). Would a photograph be enough? Are there details a photograph could not pick up that a casting method could? Cassidy (1980) describes a time where evidence collectors would opt for a photograph in order to avoid looking incompetent if their cast were to be unsuccessful. Appropriate training is needed for casting, but it is unlikely the training will equip the trainee with the experience needed to undertake a cast in all conditions they may come across. A cast that works well in one environment may have been a result of the appropriate ratio of components, but that same ratio of components may not work in a different environment. This kind of method is therefore likely to be bumped into quick and easy photography. A non-invasive digital method has therefore been a logical step forward for several years.

The trajectory of 3D research in other disciplines shows what is possible by first improving recovery which then leads to demands for better analytical tools and ultimately wider awareness. There are many forensic journals in the community, many of which offer a broad spectrum of forensic disciplines. There are no individual journals specifically dedicated to footwear evidence research, but most can be found in the Journal of Forensic Identification. This journal includes disciplines such as fingerprints, DNA, and footwear. Between 2018-2019 however, the percentage of total articles dedicated to footwear research was 2.56%, compared to 0.51% for the *Journal of Forensic Science* and 0.74% from *Forensic Science International* (Table 8). The footwear research taking place, specifically in reaction to the NRCs (2009) call for automation of pattern matching, relies heavily upon large data sets. It is this lack of data which has been attributed to the lack of research and development (Pavlou and Allinson 2009). Unfortunately, not enough data sets are available to practitioners with which to increase the quality of their work and confidence in their analysis. Many research efforts are attempted by practitioners around the United Kingdom as a side to their day-to-day roles of footwear examination as encountered on a visit to West Yorkshire Police Identification Bureau. This research is possible due to access to data but restricted due to resources. This thesis therefore aims to provide support for practitioners in the way of data and validation methods.

2018-2019	Footwear Articles % of total	Fingerprint Articles % of total
Forensic Science International	0.74%	3.27%
Journal of Forensic Science	0.51%	4.96%
Journal of Forensic Identification	2.56%	58.97%
Average (Mean)	1.27%	22.40%

Table 8. Statistics from 2018 to 2019 from three journals all covering a spectrum of disciplines within forensic science. Three journals were chosen to incorporate different journal sizes. Research papers and technical notes with mention of either footwear or fingerprints within the title were selected for these statistics.

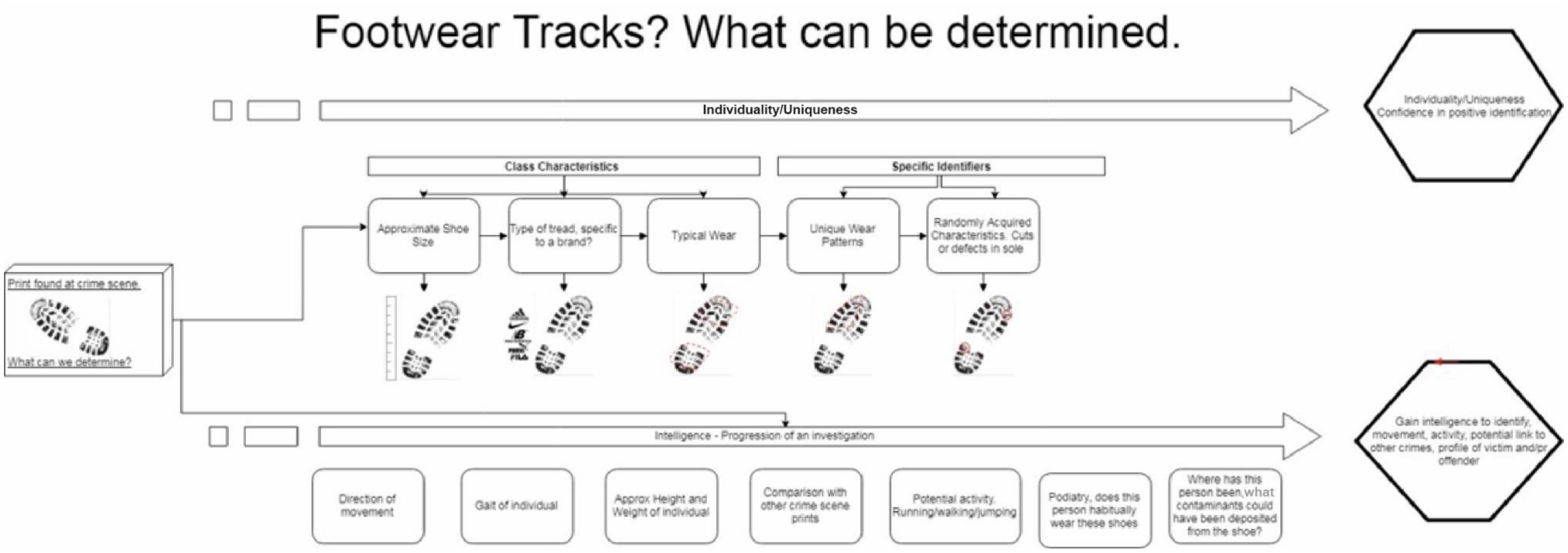

Figure 6 - What can we determine? An illustration of evidential and intelligence contribution from a footwear impression. If we were to find an impression at the scene of a crime it is important to know what we can obtain from it. This illustrates the two avenues of data potentially obtainable.

Chapter two: Methodology

2.1 Methodological approaches

The admission of expert evidence and opinions in legal proceedings, especially in the USA, has a long history of being contested. One response to this was the guidelines issued by the US Supreme Court in light of the Daubert v. Merrell Dow Pharmaceuticals, Inc. (1993) case which stated that new techniques and expert opinions need to: (1) have established methods; (2) have a known or potential error rate; (3) have widespread acceptance by the relevant scientific community; (4) have been subject to peer review; and (5) be testable and have been tested through scientific method. While subsequently modified to allow greater ‘space’ in proceedings for the forensic expert the essential point holds here (Grivas and Komar 2008). The (2009) National Research Council’s report on forensic practice in the USA emphasised the critical importance of known error rates and again called for greater scientific support for the opinion of the so-called expert.

Introducing a new technique or type of evidence without this scientific foundation can set back the contribution it can make. The development of the discipline of Forensic Podiatry (Edmond and Cunliffe 2016) and in particular, issues around forensic gait analysis illustrates the issue well. Forensic gait analysis has in the past been described as having a ’weak scientific and evidence base’ and the admissibility of such evidence has been questioned more than once (Edmond and Cunliffe 2016). For example, gait analysis, although successfully used in trials in other countries, came into question in Canada in 2008 (R v Aitken 2008). It was argued in an appeal that the gait evidence used to convict ‘lacked the requisite level of reliability’. The appeal was dismissed (Nirenberg et al. 2018) and the alleged continues to serve life in prison, however, further criticisms of the scientific base for gait analysis followed, including Otway v Regina in the UK in (2011). From the turn of the century and specifically from 2010 onwards the damage caused by this ‘shaky start’ has been steadily repaired by a succession of papers underpinning the method (e.g., Reel et al. 2010; Birch et al. 2020a; Mukhra et al. 2020). These have brought gait analysis in line with the ideals of the Daubert standards, allowing it to become a more routine and widely accepted line of evidence (Birch et al. 2020b). The lesson here is that introducing a technique into practice without a firm scientific foundation can be a problem and it is a lesson that has been heeded closely in this thesis.

If we take SfM photogrammetry to be a new forensic technique despite its widespread use in other disciplines (e.g., Bakker and Lane 2017; Brandolini and Patrucco 2019; Al Khalil 2020; Bennett et al. 2020) and its considerable heritage as an analogue based technique extending back to the early 20th Century (Albertz and Wiedemann 1995) then these principles apply. One of the aims of this thesis is to provide knowledge of error rates, limitations of application and a body of peer reviewed literature that can support the use of SfM photogrammetry for the recovery of footwear evidence. This can be approached in a number of different ways:

Global or national methods competition: One solution is to have different experts (or forensic labs) each with their own methods, essentially compete in drawing out inferences from a series of posed cases. This has value where the new techniques can be tested on a standard and identical data set. This method has the advantage of engaging practitioners directly with a series of field trials. It is similar to a handful of studies the oldest of which dates to 1996 (e.g., Majamaa and Ytti 1996; Shor and Wiesner 1999; Hammer et al. 2013; Speir et al. 2020), in which a range of footwear examiners, often with different levels of experience, were shown the same impressions and asked to draw conclusions from them. The emphasis was more on comparing levels of experience than the use of different techniques and did not embrace evidence recovery. Using an approach similar to this would aid the dissemination of the technique (and adoption one assumes if successful) but limitations lie in the unpredictability of the users and the lack of control over how testing involving recovery would be undertaken. It is easy to share traces that have been recovered to compare interpretations, but it is difficult to share crime scenes and ask experts to recover evidence.

Laboratory controlled experiments: Another approach would be to conduct a series of laboratory-controlled experiments leading to more theoretical peer reviewed papers thereby leaving more practical question of operational feasibility to practitioners should they see the value in a change of approach. The issue here is that the experiments can often seem unrealistic and distanced from the realities of practice. The results of this approach can act as a baseline, but in general does not favour adoption.

Operational and laboratory experiments: The key difference here is that at least some of the experiments should consider issues associated with operational practice. The challenge is to create scenarios and settings that a practitioner might recognise as real. The use of real crime scenes is not in most cases a practical option due to the risks of compromising casework. The next best thing is to gain experience of 'real' scenes via secondments and placements. These visits[5] provided insight into the operational setting in which a new method had to fit into and also allowed realistic scenes to be 'created' from discussion of common occurrences with practitioners. This included getting an understanding of the computational power, digital filing systems and chain of custody processes that are currently used. An overarching theme was the tendency of each department, from crime scene examiner, to expert analyst, to the forensic regulator to find challenges with one another based on evidence collection quality, record keeping, and feedback loops.

None of these methods are mutually exclusive and all are associated with potential pitfalls. In this thesis a combination of operational and laboratory experiments has been conducted and it is expected in the future that some form of method competition could be setup. In fact, this has been suggested by reviewers of some of the papers included in this thesis, although mainly on the rather prejudiced assumption that traditional methods are best, and practitioners do not need to change. One of the footwear experts spoken to whom shall remain anonymous stated that:

> "there is often a reluctance to switch to different methods if the current technique is well established and 'part of the furniture'".

Getting practitioners to engage with objective method competitions is likely to be difficult. Also doing so before all the basic operational problems and levels of accuracy and precision have been determined may simply increase the reluctance to accept the new technique. A switch in method comes with an implicit assumption that what they have been doing, often for years, has not been good enough with the intendent risk of judicial appeals.

Much of the existing scientific underpinning for SfM photogrammetry currently sits in other research communities, namely that associated with the study of fossil vertebrate tracks (Bennett and Budka 2018). Whilst it is of great benefit that this work exists, the knowledge transfer required is to be sensitively undertaken.

Increasing the quality of forensic science has, and will go on to, require many interdisciplinary connections such as the one we are faced with in the acceptance of digital recovery techniques. An example of another community who can greatly contribute to forensic science but has faced challenges in doing so, is in the field of biometrics. Meuwly and Veldhuis (2012) describe the difficulties of collaboration between the forensic sciences and biometrics as the less than successful sharing of methods between the two communities. Illustrating this is their paper simply entitled ‘From two communities to one discipline’. The requirement of articles of this nature (Meuwly and Veldhuis 2012), pulling communities together, illustrate the process which is often required. Interestingly, and as noted by Meuwly and Veldhuis (2012), the lack of analytical models describing features of footwear marks, limits the possibilities of forensic biometrics pattern recognition systems being created. This point simply illustrates that the lack of a bridge between communities halts important research. In this instance, a bridge between forensic science, SfM photogrammetry communities such as geology and palaeontology and biometrics communities, is required to collaborate if further advancements can be made for use in forensic science.

2.1.1 The way forward

In keeping with the aim of the thesis and the methodological approach outlined above, a series of experimental trials were undertaken. Ethical approval was obtained for all trials and all participants were provided with information sheets prior to giving informed consent. All participants were informed of the nature of the data collection and storage, advised that all data was anonymous and informed that they could terminate their participation in the trial at any stage. As one would expect, method descriptions are embedded in each paper, however despite the risk of repetition this chapter pulls together some of the common methods. In part this also covers work that sits outside specific papers but also as a general review of methods which might be of interest to practitioners reading this thesis.

The methods used in this thesis are a combination of lab-based and field-based experiments. This is to replicate the environments used in evidence collection, test impression environments and analysis. Following guidance from the PCAST report (2016), to establish foundational validity a method is required to have been tested under conditions appropriate to its intended use. Academic research and police procedures are not intrinsically linked. Previous research utilising unpractical scanners with limited portability and high costs has been proposed as viable recovery tools despite the obvious limitations. For this reason, throughout this thesis, many footwear impressions were recovered, be it via SfM photogrammetry, photography, or casting, in woodlands, rural areas, nature reserves, gardens and inside typical UK homes.

SfM has been used for this research to demonstrate the application of digital recovery. Whilst the methods and experiments are all focused on SfM, many of the topics discussed or data analysed could have been obtained or applied to the use of other digital recovery methods (e.g., Optical Laser Scanning; Multi-view Stereo). The introduction of digital methods can be seen around 2007 (Buck et al. 2007) within the context of recovery in snow. Seeing how other communities have worked through these more impractical digital methods (in this case laser scanning), has allowed us to move straight to a more appropriate method (SfM photogrammetry).

2.2 Methods

2.2.1 SfM photogrammetry

Broadly put, SfM photogrammetry can produce 3D structure from a series of overlapping images (Westoby et al. 2012). The mathematics behind its existence, namely coplanarity, collinearity and a self-calibrating bundle adjustment have been developed over years of photogrammetry use and research (Smith et al. 2016; Chandler and Buckley 2016). Involved in the process of SfM is the acquisition of a number of photos relative to an object or surface. Distinctive features are then ‘paired’ between each of the photos and after the application of mathematical models, produces an unscaled point cloud. The method differs from other types of photogrammetry in that there is no requirement to specify a network of targets of known 3D positions (Westoby et al. 2012). In SfM this process is automated and there is no doubt one of the reasons SfM has become so popular. The momentum of this method, across many scientific disciplines, has grown rapidly in recent years. A Google Scholar search of SfM Photogrammetry produces 14,800 results, 11,400 of which have been since 2016. SfM is widely considered to be a ‘rapid, highly flexible, low-cost, and contactless method to preserve and valorise valuable assets’ (Brandolini and Patrucco 2019, p2134) or as Scaioni et al. (2018, p1029) states it is ‘a flexible and powerful tool to provide 3D point clouds describing the surface of objects’. The recurrent words across this body of literature are flexible and low cost.

We can break the practical application of SfM to footwear recovery down into a series of steps separated below into: (1) data collection, and (2) preparation and analysis of an SfM model.

Data Collection: During the early stages of this research a photographic procedure suitable for successful recovery of footwear via SfM photogrammetry using the OpenMVG engine was established through experimentation and was then subsequently used throughout to establish consistency between experiments. This protocol is specific to OpenMVG which is the SfM engine within the freeware DigTrace and may need to be altered for other SfM engines. It is based on the guidance provided in Bennett and Budka (2018). The author concluded that the following set of guidelines gives reliable and repeatable results for all substrates.

One: Identify the impression boundaries, the use of oblique lighting may be of assistance at this stage for locating latent 3D impressions.

Two: Place a scale of known dimensions, with visible graticules, next to the impression or set of impressions.

Three: If using a digital single lens reflex (dSLR) camera, adjust the settings appropriately. They must not be changed during data collection and a fixed focal length and depth of field should be used.

Four: Take 20-30 accurately focussed photos as shown in Figure 16A. Begin taking a photo from directly above the impression taking care to include a reasonable area around the impression and inclusive of the scale. Move on to photograph from the sides of the impression at multiple oblique angles. Move closer to the impression (do not zoom) and photograph quadrants of the impression from one angle, ensuring all photographs overlap. Change angle and photograph again in quadrants.

Five: Upload the images to a computer and create a folder per impression/model. This should house all 20-30 photos for that impression or group of impressions. This should not include any blurry images or images of anything other than the impression

Six: Upload the folder to either the cloud-based version of DigTrace or the local version and begin model building.

Preparation and analysis of an SfM Model: Once an SfM model has been built, several output files are available to the user. The variety of files will be suitable for different pieces of software. Specifically, to bespoke software DigTrace, an output folder is created housing these files. To open the model for viewing in DigTrace, this output folder will need to be selected. There are several essential steps from this point that need to be undertaken to create an output that is user friendly (Steps 1-3). Following this a selection of options for analysis or visualisation purposes (Steps 4-5). Good practice for the chain of custody can be implemented at each of the stages below. Appropriate file naming and file save locations are as straightforward as any other digital files. Key to this is the availability of the raw unaltered model, to all those that encounter the evidence along the chain.

One: Auto Rotation: DigTrace has an integrated feature to correct the orthogonal plane of the model. This is simply the press of a button. This calculates the principal plane though the point cloud and rotates all points to that plane. In order to achieve a correctly scaled model, this step is crucial.

Two: Scaling: To achieve real dimensions, a user is required to input measurements of two points on the scale within a model. This is a key point of quality checking accuracy. This can then be checked at any point during model analysis.

Three: Cropping: It is often good practice to crop a model to remove unnecessary points. This can be achieved on either the x,y or z plane. This may be particularly useful if the area in which the impression is found is surrounded by long or overhanging vegetation. Removal of excessive depth points will increase the sensitivity of the depth scale and may allow for increased visualisation of features.

Four: Surfacing: A variety of experiments within this research have utilised surfaced point clouds in order to aid in visualisation of an impression. The process of surfacing involves inferring the topology of the surface, accurately fitting noisy data and filling holes reasonably (Kazhdan et al. 2006). There are numerous ways of surfacing point clouds, all with merits and limitations that need to be considered in order to achieve the best outcome for the individual model. Multiple freeware options house these surfacing options. Meshlab[9] and CloudCompare[10] were selected for use due to clear and logical user interfaces. Two common algorithms available in both Meshlab and CloudCompare were used throughout this research. The Delaunay triangulation, which creates a triangle mesh interpolating all or most of the points in the cloud (Kazhdan et al. 2006) and the Screened Poisson Surface Reconstruction method. Broadly speaking, all surfacing methods can be divided into two groups; a group that approximates points by an implicit function, this is the category in which the Poisson surface method falls, and a group that connects the points to form a surface mesh, also called interpolation methods. This is the category that the Delauney triangulation method falls within (Boltcheva and Levy 2016).

The Delauney triangulation method is operationalised in the freeware CloudCompare to achieve a surfaced look with minimal computational power. The surfacing takes a matter of seconds and quickly gives a smooth and accurate surface to an impression. Its implementation has been specifically tuned for 2.5D objects, that is surface textures and impressions. High resolution screen captures of surfaced models have been used in multiple figures to illustrate the power of digital 3D recovery tools in creating a like for like representation of the original impression. This differs from DigTrace which relies on colour-depth renders (Bennett and Budka 2018).

The Poisson Surface Reconstruction requires additional computational time over the Delauney method to process (Table 9). There are many settings which can be altered that will in turn increase or decrease the time taken for the process to complete. For each use of surfacing within this thesis, the method of choice was determined based on whichever gave a better representation of the ground truth, including textural variations and smoothness.

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[9] Meshlab: (https://www.meshlab.net/) full description of software can be found in Table 15 part of Paper 3.3.

[10] CloudCompare: (http://www.danielgm.net/cc/) full description of software can be found in Table 15 part of Paper 3.3.

The initial output of an SfM photogrammetry model consists of a raw point cloud made up of hundreds or thousands of points. This can, upon initial visualisation, appear to be a smooth surface. If you were to zoom into this output eventually you would see many holes in between these points. The process of surfacing effectively fills these points so that if you were to zoom in on the surfaced models, there would be no holes. There is, therefore, an argument that the filling of these holes takes the impression away from the ground truth in which it began, meaning the submission of a surfaced model for evidence can be a questionable idea. It was a constant consideration throughout this research that the use of surfacing can be misleading. It has therefore been signposted, wherever possible, so that any reader is aware they should always refer back to the source point cloud.

Model Type	Model	Time Taken (seconds) - Delauney 2.5D (XY Plane)	Time Taken (seconds)- Poisson Surface Reconstruction (Octree Depth 10)
Dust	1	11.7	39.3
Mud	2	8.4	47.5
Sand	3	12.3	44.6
Snow	4	5.3	31.7
Carpet	5	8.9	42.7
Blood on Carpet	6	9.7	38.1
Soil	7	7.6	46.5
Soil	8	7.2	54.3
Soil	9	8.8	48
Soil	10	7.1	45.1
	Average (Mean)	8.7	43.8
	SE	0.7	1.8

Table 9. Timings acquired through repeated use of Delauney and Poisson surfacing methods. Various models of various point cloud sizes were used for these tests.

Five: Comparison of Raw or Surfaced Point Clouds*:* There are a variety of methods available to compare 3D surfaces (Girardeau-Montaut et al. 2005) and the method used throughout this thesis draws on the mathematics of Felix Hausdorff. Hausdorff Distances as they have become known, provide a method for comparing meshed or rendered surfaces based on the distance between neighbouring points. This method was chosen due to the higher precision it offers over other methods (Girardeau-Montaut et al. 2005; Charbonnier et al. 2013; Figure 7). Using this method, we can measure the degree of similarity between any two-point clouds. Here we use the freeware CloudCompare to compute cloud to cloud distances which utilise a partial version of Hausdorff Distance calculation

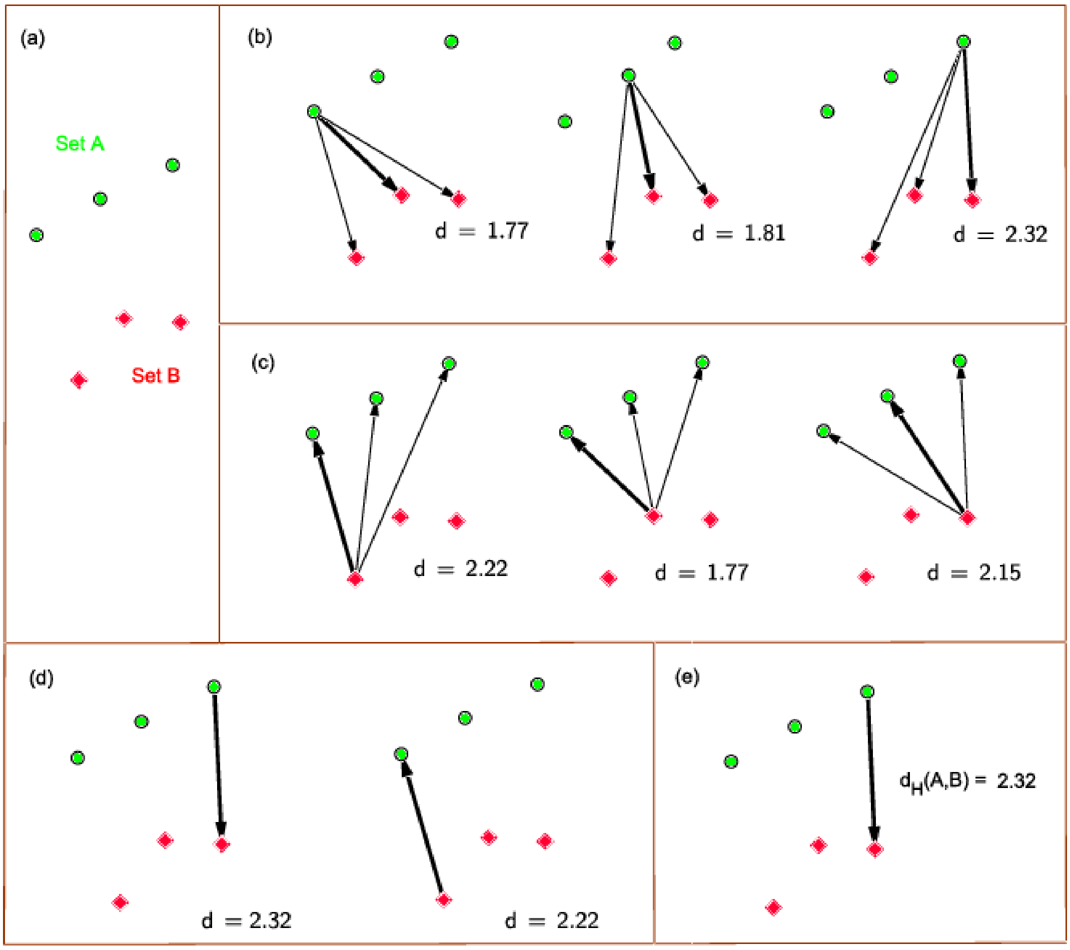

Figure 7. Hausdorff Distance for two-point sets A and B. **(a)** The point sets. **(b)** Computation of the Euclidean distance from each element of the point set A to each point of B. **(c)** Computation of the Euclidean distance from each element of the point set B to each point of A. **(d)** Maximum distances between sets. **(e)** Hausdorff Distance between set A and B (after: Charbonnier et al. 2013)

Step One: Two different point clouds are imported into CloudCompare and aligned both in the x-y and z planes. A rough alignment was first undertaken using a system of matching points and with a minimum of 10 points being used in each case evenly distributed across the whole surface (i.e., including toe area, mid-area, and heel area of model). This is simply a matter of matching identifiable landmark features on both point clouds. A fine alignment using an iterative closest point (ICP) algorithm was then applied. This matches each point in the source cloud to the closest point in the reference cloud and brings them together in alignment.

Step Two: Approximate cloud to cloud distances were then measured (Mesh to Mesh comparisons can also be achieved if a point cloud has been surfaced). This computes the distances between adjacent points on the two clouds using a 'nearest neighbour' method. The first output is an option which reduces the maximum distance between the points reducing computational drain and since the distances are low, the maximum distance is selected, and the process runs again. The results are shown in a scalar colour field and the standard deviation and means of the distances reported.

2.2.2 Materials

Details of all materials are discussed in each relevant paper. Detailed below are the material considerations considered upon undertaking this research.

Shoe choice

For a large part of this research, trainers were used to create impressions for modelling. This choice was based on a general understanding that trainers are a keen choice of shoe for 'typical' criminals. Informal figures in national newspapers and online blogs report of the 20,000 shoe prints on record in 2010, 90% came from trainers (Clements 2007). They also report on the top ten shoes worn by suspects which are all trainers.

For specific experiments it was, however, useful to know the shoe that was number one on this list at the time the experiment began. Providing data on the nature of wear of this particular shoe would be arming practitioners with as much detail as possible to aid their analysis. It therefore made logical sense to choose the shoes they see most frequently. Information from the National Footwear Database[11] as of 2018 showed the most frequent shoe to be a Nike Air 90. Multiple pairs of this make and model were subsequently purchased for this research.

Test impression medium (Two Dimensional)

Inkless shoeprint kits[12] (Figure 9) and an Everspry Shoeprint Scanner[13] (Figure 8) were used for any element of this research that required a 2D record of a shoe sole. Typically known as ‘BigFoot’, the inkless shoeprint kit (or variants thereof) has been used in multiple studies (e.g., Kennedy 2005; Reel et al. 2010; Reel et al. 2012). The process requires a shoe to have an inkless dye applied (by walking or placing over an inkpad) and the shoe then either placed (for static) or walked (for dynamic) over a piece of chemically treated paper. The Everspry Scanner is linked to a computer and requires someone wearing shoes to walk over a pane of glass with a camera underneath. The output is a digital file that shows any part of the shoe sole that met the scanner. Standard practice for 2D test impressions in a laboratory setting would be the use of powder to create either a static or dynamic (or both) impressions onto acetate. This would then be sealed, and the output could easily be overlayed onto a questioned print to aid in the analysis process. This comparison aspect was not required for this research and inkless pads or the Everspry scanner were therefore used due to their overall practicality.

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[11] Details provided by Julie Henderson, Detective Superintendent, Bedfordshire Police 07/12/2018

[12] https://www.csiequipment.com/shoeprint-inkless-kit_p31581.aspx

[13] http://www.everspry.com/en/products/products_03.htm

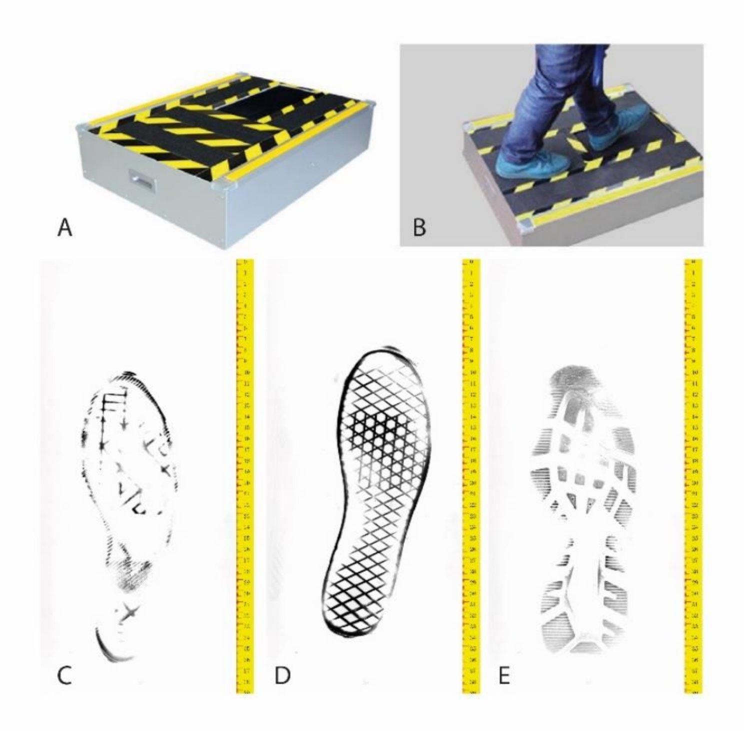

Figure 8. EverSpry Footwear Scanner[13] and example outputs. **A.** Scanner. **B**. Example of how a user walks over the plate. **C, D** and **E**. Example outputs with a variety of trainers.

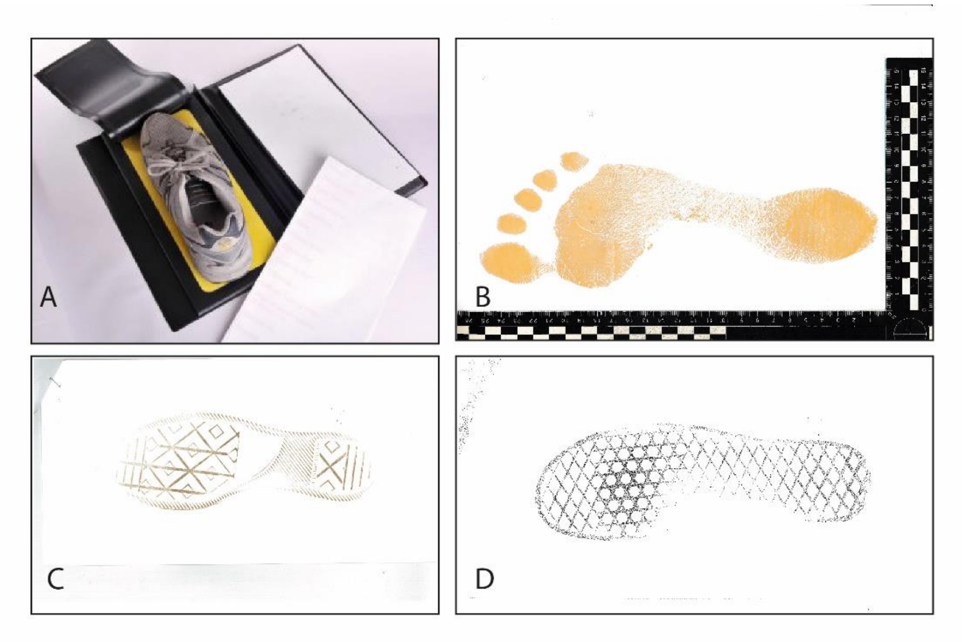

Figure 9. Inkless shoeprint kit[12] and example outputs. **A.** Components of kit include inkless pad and chemically treated paper. **B.** Example output of a barefoot impression. **C**. Example output of a converse shoe. **D**. Example output of a Vans shoe. Note the difference in colours is a result of the age and moisture levels of the kit.

Test impression medium (3D)

Test impressions are an important part of the examination of footwear evidence (Shor et al. 2018). They are made from a suspect's shoe in a laboratory and are used in comparison with crime scene materials. The test impressions need to have been prepared in the same way as exhibited at the scene, which includes many variables, in order to make a reliable and robust comparison (Farrugia et al. 2012). Limited research has been undertaken investigating the ability to replicate these variables, but studies have shown that factors such as pressure can be replicated with a test rig to better match the pressure exerted at the scene (Farrugia et al. 2012). Shor et al. (2018) has also offered a compelling study that shows an apparent variability in test impressions that may mislead a comparison. Despite the limited research into test impressions, they remain a critical part of the process.

The production of 3D test impressions can create more challenges than 2D where materials and contaminants are often easier to replicate in a laboratory. The current method of obtaining a 3D test impression is BioFoam™[14], a product that enables the examiner to push a suspect's shoe into a foam surface and leave a 3D impression in which to compare to a cast collected at a scene. This has obvious limitations as impressions in different substrates will have inherent variations.

Bubber™[15] (Figure 10) is a children's modelling compound akin to the many of the kinetic sand varieties currently available in the market-place. LeMay, (2010) compared it with one of the leading 3D test impression materials BioFoam™. LeMay (2010) concluded that Bubber™ revealed finer detail than BioFoam™ and had a host of practical advantages over it. Bubber™, unlike commercial or home baked playdough, does not dry out. It was therefore used throughout this research as a test impression medium. A further advantage of using Bubber™ is the ability to mix different colours together, thereby improving the quality of the SfM models produced. Preliminary studies undertaken by the author show a marbled finish, produced by mixing different

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[14] https://www.csiequipment.com/bio-foam_p31486.aspx

[15] https://www.amazon.co.uk/BUBBER-Unique-Modelling-Compound-Bucket/dp/B0029XML3U

colour of Bubber^{TM} gave better SfM results when compared to a single colour or to BioFoam^{TM}. Table 10 provides a comparison of the two products based on experience gained in this research.

	Bubber^{TM}	BioFoam^{TM}
Advantages	Reusable therefore reduced costs	Easy to cast
	Easy to Store	Easy to use, no physical requirement other than an open box.
	Easy to cast	
	Easy to produce digital models via photogrammetry	
	Large surface areas can create a good environment for obtaining dynamic impressions	
Disadvantages	Physical requirement to mix colours (if producing photogrammetry model)	One time use only increases the associated costs.
	Physical requirement to roll out new sheets for each use	Requires large storage spaces
		Doesn’t lend itself to some methods of digital modelling due to low textural variation and a container that obstructs camera angles.
		Not Recyclable
		Rigid containers provide limited room for undertaking dynamic impressions

Table 10. Advantages and disadvantage of Bubber^{TM} compared to Biofoam^{TM} as a test medium for 3D footprints, based on experience gained in this research.

Figure 10. A range of examples of impressions created using Bubber^{TM} **A.** Photograph of shoe impression in Bubber^{TM} **B.** 3D model of shoe impression in Bubber^{TM} **C.** DigTrace colour render, viewed in orthogonal plane, of shoe impression in Bubber^{TM} **D.** Bubber^{TM} packaging. **E.** Photograph of key impression in Bubber^{TM} **F**. DigTrace colour render, viewed in orthogonal plane, of key impression in Bubber^{TM} **G.** Photograph of a tool **H**. Photograph of section of tool **I.** Photograph of Tool impression in Bubber^{TM} **J.** DigTrace colour render, viewed in orthogonal plane, of tool impression in Bubber^{TM}

Considerations of gait

A volunteer may change their behaviour and performance consciously or unconsciously during a test (e.g., Yantz and McCaffrey 2005) when observed. If you ask an individual to leave a test impression, or to place a foot on a target while walking, there is a good chance that they will become self-conscious and modify their stride or gait. It was a phenomenon observed by the author while supervising undergraduate forensic data collection exercises. For this reason, many impressions were made by the author or a limited pool of volunteers to (1) minimise the 'stage-fright' effect, and (2) to reduce the number of gait types (and associated variance) within the study. In addition, extensive use was made of 'unknown' traces left by passers-by. While vital data on walking speed, sex, weight and age of a trace are unknown such traces can be considered 'natural' traces. They were accessed by making use of muddy paths, the edges of grass verges and other similar impression-bearing surfaces of opportunity. This allowed a large data set of natural impressions to be built up showing a range of behaviours and shoe types.

Wherever possible dynamic footwear impressions were used in the experiments reported in this thesis, because they are most likely to represent the traces left at crime scenes by suspects travelling to or from a scene. Barefoot literature tells us that differences in basic foot dimensions have been noted depending on whether a trace is placed (static) or left during normal walking (dynamic: Reel et al. 2012; Mukhra et al. 2020). This has been assumed to be reflected in shod impressions throughout this project and due care has been taken when obtaining impression data. Barefoot impressions were not initially considered relevant to the project which focused mainly on 3D traces in Europe and the Americas where people are for the most part habitually shod. However, in light of the discovery of latent 3D carpet traces barefoot impressions were considered (Paper 3.5).

Casting

Casts of all footwear impressions in this thesis were made using current and advised methods as set out in the UK National Policing Improvement Agency

(NPIA) Footwear Marks Recovery Manual (2007) with small modifications in alignment with the casting material manufacturer's instructions. Precisely 1kg of dental plaster was measured (material properties can be found in Table 30) and stored in large Ziploc bags. This amount was always more than enough to cover every impression sufficiently. Each bag per footwear impression was used with precisely 600ml of water poured into the bags and mixed by hand for a minimum of three minutes. Once the consistency of the dental stone 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 or card dam was used to hold the plaster in place. The dental stone was then left in the impression for a minimum of 45 minutes. The cast was then removed and placed in trays and any adhering substrate removed with a soft dry brush. All casts were then left to air dry for a minimum of 72 hours on drying racks allowing air to flow around all of the cast. The cast then underwent further cleaning under a tap, again with a soft brush.

Chapter three: SfM photogrammetry and footwear

Having established in the previous chapter a methodological approach and an outline of the key methods, this chapter aims to examine SfM photogrammetry as a recovery tool for 3D footwear impressions through a series of empirical studies (Table 11). The methodology focuses on both operationally relevant scenarios as well as laboratory experiments with the aim of establishing the following: (1) overall reliability, accuracy and precision of SfM photogrammetry with specific application to footwear recovery; and (2) SfM reliability specific to different types of environments in which 3D footwear is commonly recovered. The aim is not just to show the basic functions of SfM recovery but to introduce the reader to some of the more challenging aspects of footwear recovery and the potential contribution that SfM can make to these challenges.

	Paper Title	Research Questions Addressed
3.1	(Unpublished Technical Note): Accuracy and Precision – A practitioners' guide	1,2
3.2	(Unpublished Technical Note): SfM Photogrammetry Software Review	1
3.3	Technological Innovations in the recovery and analysis of 3D forensic footwear evidence: application of SfM	1,2,3
3.4	Empirical evaluation of the reliability of photogrammetry software, in the recovery of 3D footwear impressions	1,2
3.5	Recovery via SfM photogrammetry of latent footprint impressions in carpet	2,7,8
3.6	Recovering of 3D footwear impressions from sandy substrates: technical note on the contribution of SfM photogrammetry	2,7
3.7	(Unpublished Technical Note): Use of contrast spray in the recovery via SfM photogrammetry of snow impressions.	1,2

Table 11. Contents of chapter three addressing specific research questions (Table 1).

The first two entries in this Chapter are short technical notes which currently remain unpublished. Paper 3.1 details a method for determining the precision and accuracy of SfM, and for that matter any forensic method. This method appears in several different papers within this thesis, but is included here with a complete and currently unpublished set of results (i.e., parts are included in various papers but not all the data is published).

Paper 3.2 addresses the suitability of photogrammetry freeware DigTrace, in the context of a forensic application. This bespoke software has been specifically designed for the use of recovering and analysing fossil footprints and footwear traces (Bennett and Budka 2018). It is, however, not a commercial product and it was therefore deemed appropriate that a brief comparison against alternative software, including the current industry-standard, was appropriate.

Paper 3.3 explores the practical application of SfM methods via several small-scale experiments, which are intended to help guide future practitioners. This paper follows an instructional theme and as one document, provides the forensic community with reference work for future forensic photogrammetry.

Paper 3.4 delivers an assessment of repeatability and reproducibility of aspects of SfM photogrammetry in a forensic context. This paper uses a point cloud comparison technique to assess variability in multiple models taken from one impression in several environments. The paper goes on to provide an assessment of reproducibility when making a model of one impression using multiple cameras.

Papers 3.5 and 3.6 examine the recovery of 3D footwear in substrates traditionally considered to be challenging, namely carpet and sandy substrates. The work on carpets (Paper 3.5) also touches on the recovery of barefoot impressions common at indoor crime scenes. Paper 3.6 presents SfM as a method, either applied on its own or in conjunction with a current method that can be easily utilised for a very common substrate in the UK. An impression found in an area of loose sand/grit does not lend itself well to traditional casting rendering successful recovery most likely limited to 2D. A digital method in this instance shows great promise.

This chapter is concluded with a short unpublished technical note (Paper 3.7) on an aspect of the use of SfM photogrammetry when recovering snow impressions. Snow has been highlighted throughout as the most challenging of mediums. An assessment of one method aimed at increasing the quality of digital evidence is therefore included.

3.1 Unpublished Technical Note 3.1: Accuracy and precision for 3D footwear recovery methods: A practitioners' guide

Status: Unpublished technical note. Elements of this data and approach are issued in Papers 3.3 and 4.1, but not a complete set of results.

Contributions: The approach was conceived by Bennett and Larsen during supervisory discussions and operationalised by a Matlab^{TM} script written by Budka which was tested/developed iteratively by Larsen. The analysis and writing-up was completed by Larsen.

Abstract

The development, at least in the UK, of various accreditations of forensic methods (Wilson-Wilde 2018) set out the need for clear procedures by which accuracy and precision of any method can be established. This technical note proposes a procedure applicable to any footwear recovery method, including SfM photogrammetry. It can be implemented by any practitioner irrespective of their own practice, protocols or equipment. The method proposed uses basic sampling theory to determine precision rates for one-time capture. Predicted error scores show high levels of precision across 2D and 3D footwear recovery techniques including SfM photogrammetry and laser scanning, 2D photography and digital callipers. The comparison of these scores gives insight into the suitability of recovery techniques across the footwear discipline.

Introduction and background

The need for research and better reporting of accuracy and precision of forensic techniques was clearly laid out in the US National Research Council's 2009 report (NRC 2009). It is an expectation that has been in place since the origin of the Daubert Rulings in (1993) which emphasised the need for a scientific foundation for any forensic method. The NRC (2009) report was critical of pattern matching disciplines showing reliance on expert testimony, including footwear.

Similar expectations, namely to increase statistical analysis, fell on several disciplines, one of which was forensic podiatry. This particular discipline has seen responses such as those by Reel et al. (2010) who provide a discussion and protocol for determining reliability analysis in barefoot prints measurements. This contribution can be mirrored in forensic footwear. The method utilised to determine reliability by Reel et al. (2010) is the interclass correlation coefficient (ICC). This method is recommended in medical research to assess reliability in particular of inter-operator variance (Bobak et al. 2018). It effectively involves using multiple regression analysis of results obtained by different methods and/or operators to determine variance and or reliability. In theory an ICC method could have been used here but experimentation with this approach showed little sensitivity and the results are difficult to translate into a specific value for both accuracy and precision. We also wanted a method that could be easily used by any practitioner without knowledge of or access to relevant statistical packages.

The approach developed (script available upon request) allows precision rates to be determined for different recovery methods that yield dimensional measurements. There is extensive literature on accuracy and precision (PCAST 2016) but no specific guidelines or standard methods for the recovery of trace evidence. Determining levels of precision is a particular challenge for forensic recovery where a trace is often only recovered once, either because of time or more commonly because recovery leads to the destruction of that evidence (Bodziak 2017). In the laboratory precision would normally be determined by repeating a measurement multiple times to obtain a mean, median and error margins around both. You cannot do this when lifting 2D trace with a gel-lift or casting a 3D track/s because the process is destructive.

In our context accuracy (A) can be defined as the absolute departure in terms of size, shape, and texture of a recovered trace from the original. It has a range of component parts, such as those described in Napolitano and Glisic (2018). For the context of trace recovery, the following descriptive equation is proposed here:

$$A = (E_q, P, S, O, E, T)$$

Where E_q represents the equipment used, P the specific protocol used, S the materials or software, O the operator, E those factors specific to a given environment or type of trace and finally T for time on the basis that the more time one has the less likely errors will be made. In terms of precision (P), we can define it as the reproducibility of a given recovery. Equipment, protocol, and the environment should all in theory be constant, such that we have:

$P = (O, T)^{prob}$

Where prob represents random chance, the probability that the operator (O) does something slightly different, and the time (T) taken may vary. The important point is that no one value of accuracy or precision for a technique exists, only one specific to an operator, their equipment/process, operational set-up and to the environment. Therefore, a method needs to reflect this.

The components of accuracy in relation to the application of SfM photogrammetry impression recovery are therefore the camera used to take the photographs and the accompanying scale (equipment); the adherence to the photography protocol (protocol); the SfM software that creates the models (materials or software); the crime scene examiner or individual taking the photographs (operator); the surface the footwear impression was made in such as mud or sand (environment) and the speed in which the operator follows the process, potentially effecting the overall quality.

The precision can be further visualised in the form of a crime scene examiner undertaking the process of recovering the same impression a number of times. The camera, photo procedure and surface the impression is made in, all remain the same. The precision of the results, as the equation states is therefore determinable by the probability of the crime scene examiner doing something different, including the time spent on the recovery.

Method

In order to approach the difficulties in determining precision for one-time capture techniques, a method was developed based on simple sampling theory (Murthy 1967). The error around a mean or median value should in theory decline with increasing sample size, a sample of N=2 should have greater associated error than one associated with N=20. As the sample size increases the decrease in error should cease and stabilise at a level equivalent to the potential accuracy of the technique. This will approximate some form of exponential curve as shown in Figure 18. If we know the shape of this curve then we can use it to forecast the errors associated with N=1, that is a level of precision for one-time recovery. We can also use the stable line obtained post N=20+ to establish a limit to the accuracy that can be achieved.

This procedure involves replicating a series of measurements between 30 and 50 times. In most cases minimum error values are obtained after 15 to 20 repetitions. In terms of footwear traces recovery can be obtained via: 2D photography, a 3D SfM model, or by casting. Direct measurement of the trace is also possible but limited to length and width so was not included. To aid this initially, and to provide an absolute standard, a series of footwear impressions were made in a shallow tray filled with concrete. Subsequently, natural tracks were selected in different environments for the same purpose and used as test impressions (Figure 11). Landmarks were pre-placed on the concrete tracks (‘known points’) using an indelible marker in or in the case of natural impressions identifiable points were located and annotated on a photograph of the impression taken in the field. Measurements were made both parallel and transverse to the long axis of the footwear impression using the ‘known points’ and in addition overall length and width measurements were made.

In the case of 2D photography the concrete track, or identified trace, was photographed using a tripod from above. Between each of the 50 photographs the tripod was moved and reset. Photographs were scaled in Adobe Photoshop^{TM} according to standard forensic practice (Reis 2007), and measurements made between the landmarks placed. The maximum length and width of the trace was also measured. This process was repeated for each of the 50 photographs. In the case of the SfM model a concrete track (as seen in Figure 18) was placed outdoor in good light. A total of 30 photographs were collected using the standard protocol for SfM recovery (Figure 24). Between each set of photographs a break shot was taken and the operator stood up and walked away from the cast. This process was repeated 50 times, giving a total of 1,500 photographs. The photographs belonging to each model were then uploaded to DigTrace and the 3D models built. Having built all 50 models each was scaled, autorotated and digital measurements taken between the known points and for the overall length and width of the track (Bennett and Budka 2018). In some of the natural environments the number of models/repetitions was reduced to 30 to avoid any changes in the impression over time due to natural conditions, such as melting snow. The concrete test impressions were also scanned 50 times using a Next Engine optical laser scanner[16]. Note the scans are pre-scaled by the scanner.

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[16] www.nextengine.com

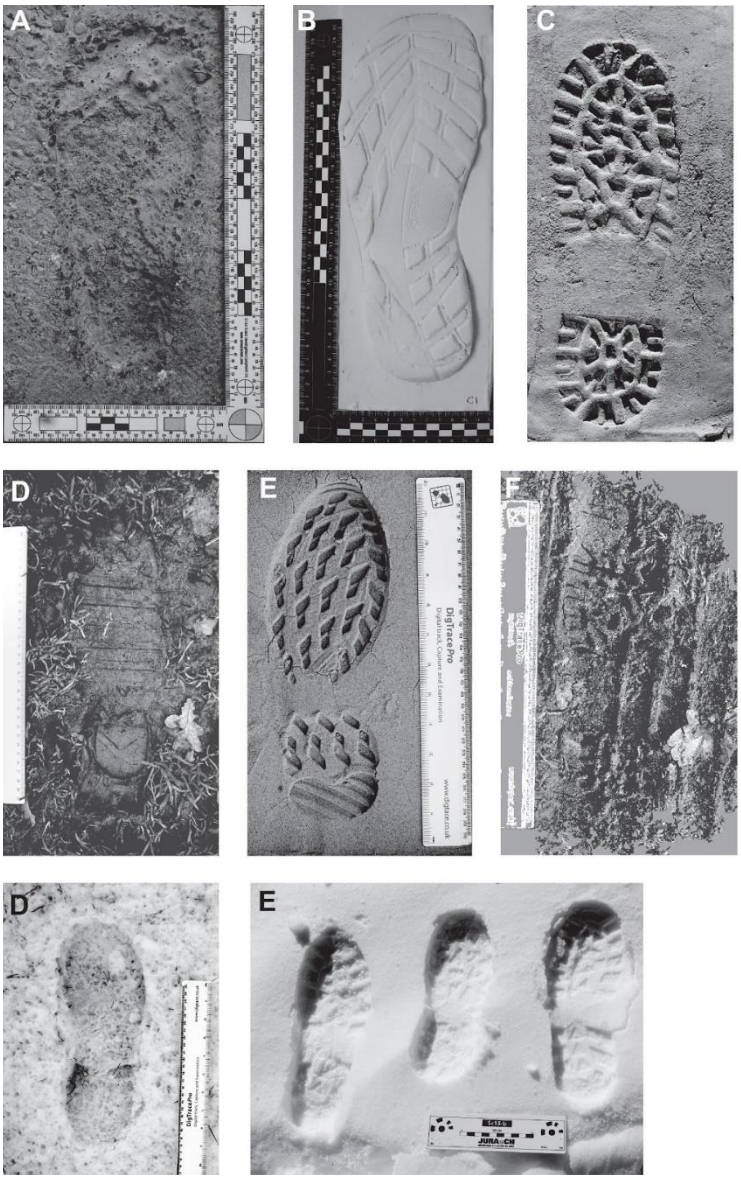

Figure 11. Shoeprints used in this study. **A** Barefoot concrete track. **B** Plaster case made from a latex mould of an outsole. **C** Concrete boot print 252 mm long. **D** Natural impression of a Wellington (Rubber) boot, note the overprinted dog track at the distal end. **E** Shoeprint in sand. **F** Vertical view of a 3D point cloud of a muddy impression of a boot and bicycle tracks. **G** Snow impression in damp thawing snow. **H** Boot impression in fresh snow.

Applying this method to casting was more challenging due to the destructive nature of the process. A latex casting medium was placed in a shallow tray and a shoe placed in it, once dry the mould was removed from the shoe to create a footwear impression that could be cast with dental stone multiple times. Using a consistent and standard procedure 50 dental stone casts were taken from the mould being careful to avoid damage when releasing the mould. The sides and base of the mould was supported within a rigid tray to avoid any lateral flex in the mould. The mould was inspected for damage after each cast and none was observed. Methods obtaining 2D records were also included. An Everspry 300 DPI Footwear Scanner (Figure 8) was connected to a laptop and a volunteer walked dynamically over the scanners plate 50 individual times. Care was taken to ensure the walking style was consistent with the user stepping onto the scanner, onto the plate with their right foot and off again in one swift motion. Adobe Photoshop^{TM} was used to carry out the measurements from the images supplied by the scanner. An inkless shoeprint kit (Figure 9), as used in many studies for the collection of data and in custody suites across the country to collect impressions from known subjects had 50 repeat prints taken. The volunteer was required to step onto a pad which coated the bottom of the shoes in an inkless dye. Care was taken to ensure each print had a similar level of coating. The volunteer then walked across a piece of chemically treated paper. Once again, care was taken to ensure the walking style was natural and dynamic. The user would walk a number of steps before and after stepping onto the paper in line with the midgait method of data collection, a traditional method of collecting foot pressure data (Orlin and McPoil 2000). If any prints were smudged or not fully contained by the page, they were discarded and repeated. The prints were then measured directly from the paper using Digital Callipers (Yosoo 300mm; ±0.03mm stated accuracy). For each experiment five repeat measurements of a given length were taken and averaged (mean).

The analytical procedure employed to process this data consists of the following steps, which were performed using a MATLAB script[17] (Further explanation of this process can be found in Paper 3.3).

One: Generate K = 100 bootstrap samples (with replacement) for each value of N in the range between 2 and 50

Two: Calculate the Standard Error (SE) for each bootstrap sample and each value of N (scatter plot in Figure 18B)

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[17] https://github.com/bosmart?tab=repositories.

Three: Derive the mean and standard deviation from SE values for each value of N

Four: Fit polynomial curves to the means and 95% confidence interval (CI) boundaries of the normal distributions calculated in Step 3 above (the CI values were clipped at 0 prior to curve fitting, see the solid and dashed lines in Figure 18B)

Five: Estimate the SE and its CI's for N=1 by extrapolating the curves obtained in Step 4 above.

Separate to the topic of precision and the application of the above method, are simple efforts in confirming technique accuracy. Whilst this is still a challenge for some methods, this can be easily addressed when specifically looking at SfM photogrammetry. Quick and simple accuracy tests can be undertaken as per the method below.

A simple method for determining accuracy in the context of SfM photogrammetry involves placing an object of known size into a digital 3D model. This is a critical step in any model creation (as discussed in paper 3.3). This is achieved when a scale, such as a ruler is placed next to a footwear impression. The entire model is then scaled to the measurements as seen on the ruler and measurements can then be provided for any part of the model. A notable advantage of photogrammetry in this context is the placement of the scale. Generic crime scene quality photography requires a scale to be properly placed on the same plane as the impression. For most 3D impressions this often means placing the scale on multiple planes and taking multiple images (NPIA 2007). This is not a requirement needed for SfM photogrammetry (Bennett and Budka 2018), ground truth measurements can be applied to the whole model through simply placing the scale next to the impression so that it is fully captured in the model.

A benefit of the scaling feature within DigTrace is the ability to repeatedly test the accuracy of any part of the model in respect to the ground truth of the scale. This can be done at any point throughout the analysis process to confirm the accuracy of the model as it changes hands during the evidential process. A further accuracy test and one not required for every model is to test the accuracy of the third plane (z). To do this we can use a known object that has three dimensions. A Lego^{TM} or Duplo^{TM} brick is well suited for this purpose due to their straight edges and consistent measurements. As illustrated in Paper 3.3, creating an impression with a Duplo^{TM} brick into a medium such as Bubber^{TM} (LeMay 2010) allows distances to be scaled and accuracy confirmed in the third dimension.

Results

The results of the precision model show 3D subjects have the highest predicted error scores when using the casting technique and SfM photogrammetry in a particular type of mud environment (Table 13). The overall results for SfM photogrammetry are encouragingly small and the errors associated with higher rates are generally around model quality. For one particular mud model (Mud-1), the levels of moisture in the environment has affected the error score, the model was of an impression made in wet mud not long after a spout of rain. The reflective nature of any water pools in the impression reduces the number of points in a cloud, reducing its overall quality. This in turn makes measurements slightly harder to obtain and the resulting higher error rates are seen.

Higher levels of error are predicted for multiple 2D recovery techniques. The slight change in methodology for these techniques allows an insight into their repeatability. Both the Everspry Shoeprint Scanner and the Inkless Shoeprint Kit had 50 separate prints obtained, whilst other methods used the same input to create 50 repetitions. This data was obtained to highlight the variance expected when either of these apparatus' are used in a custody suite to collect known impressions, which is an area of footwear evidence that is not stringently tested for scientific validation.

			Operator	Environment
2D	Inkless Shoeprint Kit		Operator 1	Lab - Controlled
	Everspry Scanner		Operator 1	Lab - Controlled
	Photography		Operator 1	Lab - Controlled
	Digital Callipers		Operator 1	Lab - Controlled
3D	Next Engine		Operator 1	Lab - Controlled
	Casting		Operator 1 + 2	Lab - Controlled
	DigTrace	Orange sand	Operator 1	Lab - Controlled
		White sand	Operator 1, 2 + 3	White Sands, New Mexico
		Mud-1	Operator 1	UK
		Mud-2		
		Mud-3		
		Snow-1	Operator 1 + 2	Italy
		Snow-2		UK
		Concrete [Op-1]	Operator 1	Lab - Controlled
		Concrete [Op-2]	Operator 2	Lab - Controlled

Table 12. Details of operator and environment for each surface environment and method used in this study.

Recovery Technique/Environment	Mean Length Error (mm)	95% Maximum Length Error (mm)	Mean Width Error (mm)	95% Maximum Width Error (mm)	Mean Known Point Error (mm)	95% Maximum Known Point Error (mm)
2D						
Inkless Shoeprint Kit	2.8410	7.0672	0.3435	0.9157	0.1072	0.2679
Everspry Scan	10.9407	28.4717	0.7830	2.0146	0.1332	0.3491
Photography	0.8015	2.1277	0.4023	2.0189	0.8015	2.1277
Digital Callipers	0.3195	0.8137	0.2520	0.6407	0.3195	0.8137
3D						
Next Engine 3D scan	0.7747	2.1341	0.4241	1.1608	0.3537	0.8923
Casting	1.8059	5.9585	0.7370	1.9431	0.5135	1.3951
DigTrace - Orange sand	0.4593	1.1983	0.2566	0.6817	0.3515	0.9279
DigTrace - White sand	2.2770	6.0106	2.5975	6.6504	0.5800	1.7019
DigTrace - Mud 1	6.4445	17.9214	0.4031	1.0969	0.2859	0.7470
DigTrace - Mud 2	0.5013	1.3063	0.2333	0.6275		
DigTrace - Mud (Partial)	0.4002	1.0549	0.3217	0.8198	0.2431	0.6410
DigTrace - Snow 1	1.3779	3.6936	0.7942	3.2018	0.3689	0.9521
DigTrace - Snow 2	1.1387	2.9061	0.6726	1.7653		
DigTrace - Concrete [Op-1]	0.3222	0.8215	0.1718	0.4489	0.3222	0.8215
DigTrace - Concrete [Op-2]	0.3868	1.0071	0.307	0.8804	0.3868	1.0071

Table 13. Error rates for length, width and distance between known points for a single operator across a range of surface environments. Note the results of a next Engine are provided for comparison.

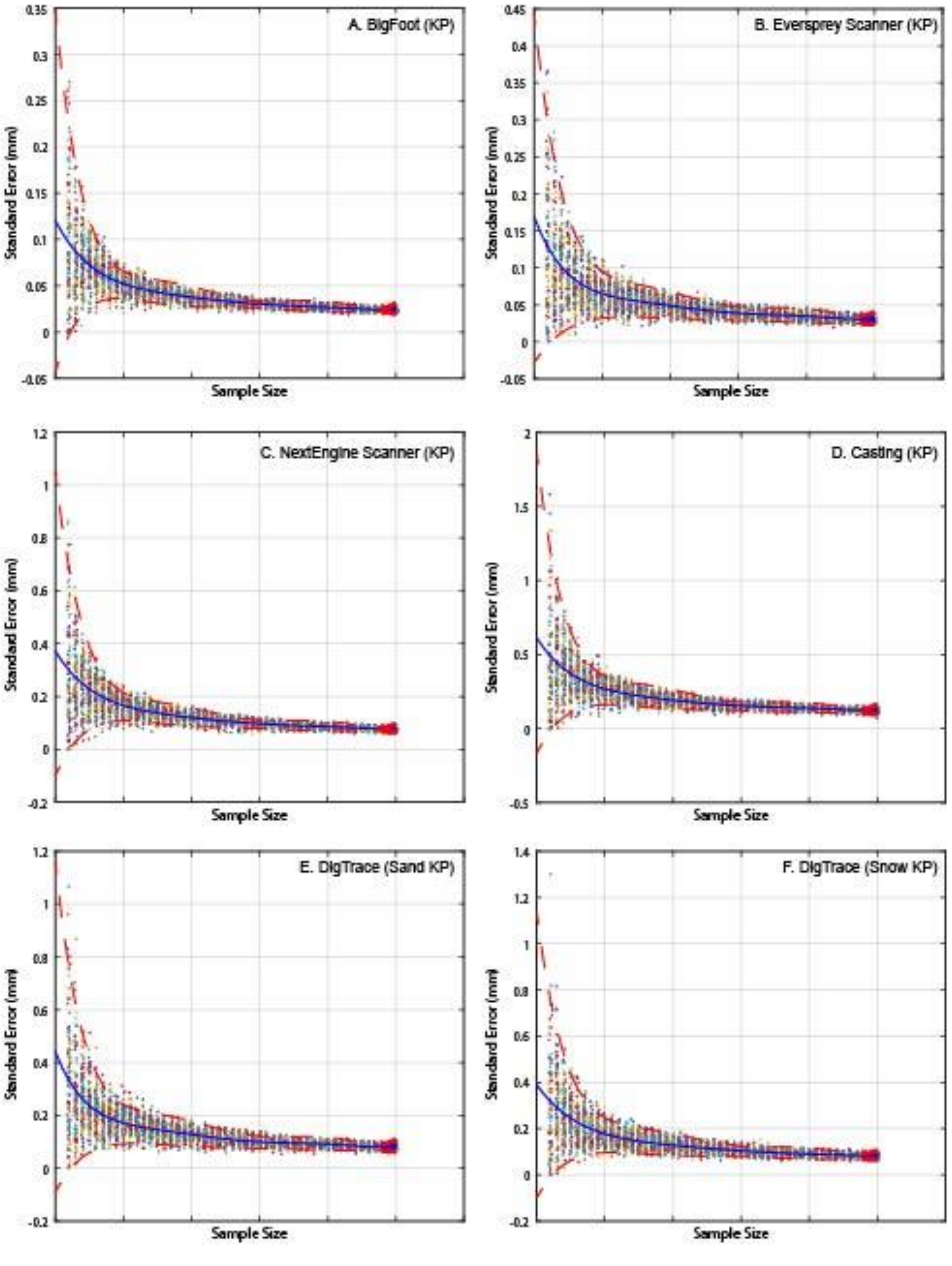

Figure 12. Graph outputs of precision method. A selection of examples using known point measurements.

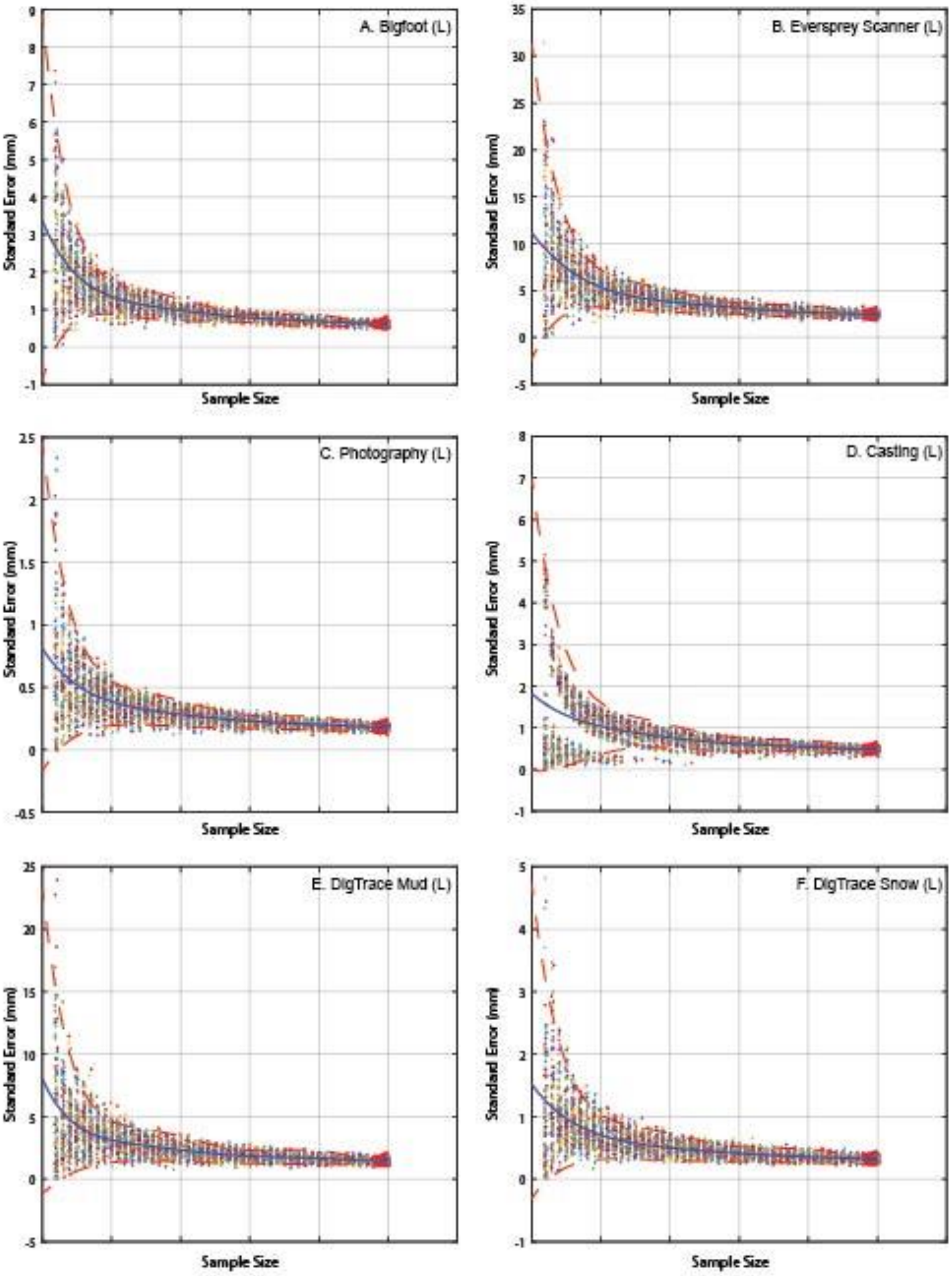

Figure 13. Graph outputs of precision method. A selection of examples using length measurements.

Discussion and conclusion

The key aim of this technical note was to demonstrate a measurement approach that can be used for all methods of digital recovery, and beyond this to other methods if appropriate, such as those used in custody suites for obtaining 2D known impressions. This method of producing error rates, like other reliability testing approaches such as ICC, can be repeated for every instance in which a new variable has been introduced. If a new user is performing the method, an impression is found in an uncommon environment, or the advent of a new piece of software or technique is introduced, the same method for determining error scores can be used, ensuring consistency in validation testing.

The results highlight that one mud environment (Figure 11) may differ in rates of predicted error than another mud environment, thus showing how the variation in environment consistencies, textures and weather conditions can all affect the recovery of a footwear impression. Such is the nature of work outdoors; it is important that practitioners are aware of the potential risks here. Blanket universal precision values attached to equipment or a method show no sensitivity to this idea and can therefore be misleading. An approach such as this described reports a value that can accompany each piece of separate evidence, with enough similarity to the original evidence as possible (i.e., who collected it, where it was collected and so on) meaning transparent levels of reporting error rates.

The introduction of digital recovery of impressions (e.g., SfM photogrammetry, laser scanning) is therefore not simply based around practical or quality advantages, but also the increased ability to perform validation studies such as this. Whilst an indication of the precision of casting can be ascertained here (further described in Paper 4.1), there is limited further testing that can be done to provide predicted error rates of casts in different environments. These limitations are perhaps more pertinent than that of the error scores themselves.

3.2 Unpublished Technical Note 3.2: SfM photogrammetry software review

Status: Unpublished technical note.

Contributions: The experiment was conceived by Larsen. Agisoft Photoscan models were built from photographs taken by Larsen by Dr Matteo Belvedere (Florence University) an expert in Agisoft Photoscan. The analysis and writing-up was completed by Larsen.

Abstract

Digital reconstruction and visualisation of surfaces is now a staple in many scientific communities. As such, there is a proliferation of photogrammetry software now available, both commercially and as freeware. To introduce digital recovery via photogrammetry into the forensic community requires some consistency in the approach and this is relevant in the choosing of the software available. It has therefore been proposed that a bespoke forensic footwear software package is a suitable way forward. To validate this software for use, it is necessary to compare against the industry standards. This is completed via the comparison of 4 models, (1) sand (2) snow (3) soil and (4) dust. All four models were built in both DigTrace (bespoke forensic package) and leading commercial package Agisoft Photoscan. A holistic comparison was made based on multiple factors. Results show that the overall quality of DigTrace models are to an acceptable standard for purpose and whilst the use of Agisoft would increase model quality, the practicality of the commercial software renders its use, in a mass sense, unattainable. That said, the use of high-quality commercial software would still be an option should an investigation require it, for example, a high-profile case where the value of the 3D footwear evidence is particularly high.

Introduction

Different types of photogrammetry software are abundant, as a quick Google search illustrates[18]. The increasing use of recreational drones is one reason for this with users demanding access to ortho-mosaics and digital elevation models. Drone Market Report (2020)[19] suggests the global drone market will

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[18] For example, this site lists the top 20 freeware solutions: https://all3dp.com/1/best-photogrammetry-software/

[19] https://www.globenewswire.com/news-release/2020/07/22/2066029/0/en/The-Drone-Market-Report-2020-2025.html

grow from $22.5 billion in 2020 to over $42.8 billion in 2025 with the fastest area being software development. There is a tradition within SfM photogrammetry specifically of freeware being developed by private individuals[20]. Many of these solutions, however, lack intuitive user interfaces as is illustrated by OpenMVG[21] which is used as the SfM engine within DigTrace (Bennett and Budka 2018). The freeware solutions are historically better than many of the commercial alternatives. Table 15 part of Paper 3.3 lists out some of the available software. Some software caters for specific types of photogrammetry such as aerial, drone mapping, or close range. The type of file output is often software specific and influenced by one's choice of pricing/licensing options. The photogrammetry blog written by Dr Falkingham[22] compares different software giving concise and informative feedback to the large choice on offer. Many of the available options are simply scripts which a user would have to find or purchase an interface to run. Choosing an option therefore relies on a user's experience and knowledge, the options available to them may then be limited to those which have a fully functioning user interface as part of the package.

Forensic providers will naturally gravitate toward commercial solutions, as illustrated by the use of Adobe Photoshop™ in most forensic cases (Reis 2007). Currently the most successful, judged by academic use, are Agisoft Photoscan and Reality Capture. These are the current leaders in the industry and produce high quality photogrammetry models with good documentation and intuitive user interfaces. Agisoft Photoscan, for example, allows a user to set a quality, which will dictate the computational input, the time in which the model can be built and the final file size of the model. They also offer automated scaling and a range of additional features. They are complex pieces of software that require professional training to be proficient.

Building a SfM model is only part of the solution, however, since once a model has been created it must be analysed and manipulated. This usually involves

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[20] Multiple entries at https://peterfalkingham.com/blog/
[21] https://github.com/openMVG/openMVG
[22] https://peterfalkingham.com/tag/photogrammetry/

a second piece of 3D visualisation software such as Geomagic or one of the other commercial solutions, although there is good freeware available (e.g., Meshlab or CloudCompare (Table 15)). The tools within commercial SfM engines and 3D visualisation software cater for all users and are not specific to forensic practice.

DigTrace was developed as freeware based on the OpenMVG SfM engine and has a series of specific tools that cater in a bespoke way for the analysis of 3D footprints and footwear impressions (Bennett and Budka 2018). It is marketed directly to the forensic community as well as to vertebrate Ichnologists more generally. It is the software that is used for the most part of this thesis. However, it is appropriate to compare this SfM engine with other commercial solutions to help practitioners make informed choices. The core question is, “is the SfM engine valid?” The aim of this technical note is to examine this question.

Method and Results

A comparison of Agisoft Photoscan and DigTrace was undertaken, with each programme being used to create an identical 3D model using the same set of input photographs. The comparative analysis was undertaken using the freeware CloudCompare which has algorithms that allow the comparison of two models, point cloud to point cloud. Detailed instructions of this process and the algorithms used can be found in Section 2.2.1

The results show a high level of similarity (Table 14; Figure 14). The largest differences can be seen in the Z (depth) plane of the models, the side walls of deep depressions such as those in sand. Agisoft Photoscan has a more comprehensive point cloud coverage in these areas where DigTrace has less. The other noticeable difference is in the soil impression where the DigTrace model has a small hole on the outskirts of the impression. This hole is not apparent in the Agisoft model. As per Table 14, the number of points present in the DigTrace Models contain around 30% of the points present in the Agisoft models. This results in significantly quicker model returns and smaller file sizes. Whilst less points may sound like a bad thing, a preliminary assessment has shown that a model can be reduced in point size by up to 80% before any visual differences begin to occur. The reduction or decimation of points cannot, however, all be in the same small area as this will result in a hole. Further work, lying just outside the scope of this project, could look to assess the level at which a model can be decimated but remains a quality high enough for a forensic investigation.

Compare	Total Points	to	Total Points	RMS	Mean Difference	Std Dev	Max distance	Notes
Dust DigTrace	776114	Loose sandy stone Agisoft	2464850	0.644819	0.30865	0.144138	1.90727	Good coverage throughout, no large gaps resulting in max distance low
Soil DigTrace	605176	Mud Agisoft	1867804	0.814948	0.287068	0.247665	6.79586	Hole in DigTrace model creating larger max distance, not in impression, on outskirts as per Figure 14
Sand DigTrace	1143854	Sand Agisoft	3395973	0.765747	0.185514	0.175499	3.38356	Good coverage throughout, no holes, highest level of difference found on the sides of deeper pattern tread

Table 14. Data obtained from comparison between freeware DigTrace with commercial software Agisoft Photoscan. Including cloud to cloud comparison statistics, point cloud totals and descriptive differences.

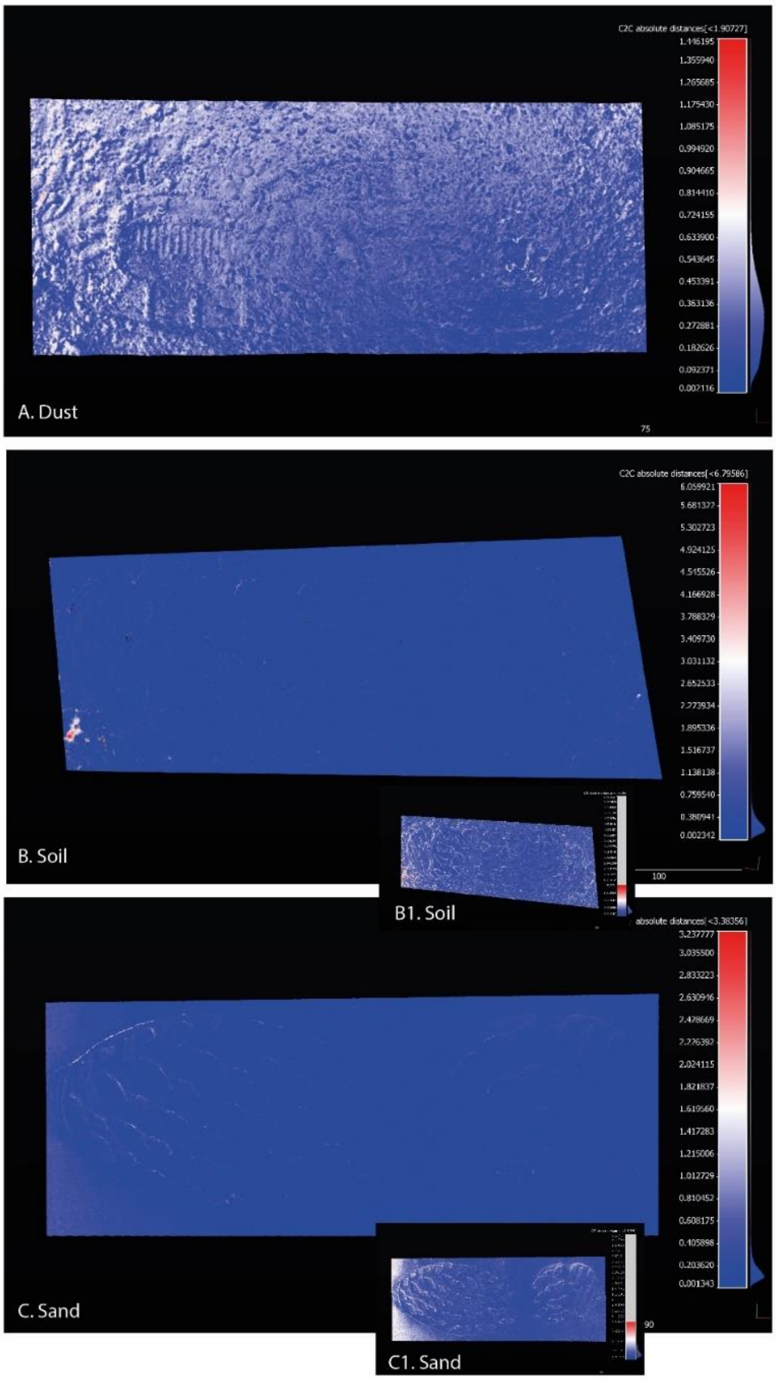


Figure 14. Cloud Comparisons between Agisoft output and DigTrace output **A.** Software Comparison using an impression in a dusty sand/soil. **B.** Software comparison using an impression in soil. **C.** Software comparison between an impression in sand.

Discussion

It is the opinion of the author, based on a visual assessment of all pairs of models, that the differences in the software are negligible when considering the practicality of continued use of Agisoft. This includes a large cost for the software, the storage required for large model sizes, and the time taken to run each model. It is expected that some experts, judges, or jurors would simply expect the best quality software to be used on all occasions. They should be reassured that it is not the practicality that is forcing the use of 'lower quality' software, but it is simply unnecessary in most circumstances. This is evidenced in the large body of high-profile scientific literature which uses software such as DigTrace (Altamura et al 2020; Bennett et al. 2020). The key takeaways from this small study are: (1) The analytical tools available for digital 3D models are of great potential for the method, regardless of software used. Practitioners can quality assure models and provide clear and understandable assurances to the courts in the name of scientific validity. The second takeaway (2) is that if a poor-quality model is put forward for evidence, having been created and analysed in lower quality software, the potential remains for the model to be re-run in higher quality software. The input photographs will be safely stored alike any other evidence type.

3.3 Research Paper 3.3: Technological innovations in the recovery and analysis of 3D forensic footwear evidence: application of structure from motion

Status: Manuscript accepted by Science and Justice on 06th March 2021 subject to minor revisions.

Contributions: The paper and associated experiments were conceived by Larsen during supervisory meetings with Bennett and Budka. The data was collected and analysed by Larsen. The text was drafted by Larsen with editorial input from Bennett and Budka.

Abstract

The recovery of 3D footwear impressions at crime scenes can be a challenge but can also yield important investigative data. Traditional methods involve casting 3D impressions, but these methods have limitations: the trace is usually destroyed during capture; the process can be time consuming, with a risk of failure; and the resultant cast is bulky and therefore difficult to share and store. The use of SfM photogrammetry has been used widely to capture fossil footprints in the geological record and while there is a small body of work advocating its use in forensic practice the full potential of this technique has yet to be realised in an operational context. The availability of affordable software is one limiting factor and here we report the availability of a bespoke freeware for SfM recovery and subsequent analysis of for footwear evidence (DigTrace). Our aim here is not to provide a rigorous comparison of SfM methods to other recovery methods, but more to illustrate the potential while also documenting the typical workflows and potential errors associated with an SfM based approach. By doing so we hope to encourage further research, experimentation and ultimately adoption by practitioners.

3.3 Research Paper 3.3: Technological innovations in the recovery and analysis of 3D forensic footwear evidence: application of structure from motion

See:

Larsen, H., Budka, M. and Bennett, M. R., 2021. Technological innovation in the recovery and analysis of 3D forensic footwear evidence: Structure from motion (SfM) photogrammetry. *Science and Justice*. (In Press).

https://eprints.bournemouth.ac.uk/35616/

3.4 **Research Paper 3.4: Empirical evaluation of the reliability of photogrammetry software, in the recovery of 3D footwear impressions**

Status: Published 14th May 2020. Larsen, H.J. and Bennett, M.R., 2020. Empirical Evaluation of the Reliability of Photogrammetry Software in the Recovery of Three-Dimensional Footwear Impressions. *Journal of Forensic Sciences*. Volume 65 issue 5 1722-1729.

Open Access Link: https://onlinelibrary.wiley.com/doi/full/10.1111/1556-4029.14455

Contributions: The paper and associated experiments were conceived by Larsen during supervisory meetings with Bennett and Budka. The data was collected and analysed by Larsen. The text was drafted by Larsen with editorial input from Bennett.

Abstract

This paper examines the reliability of SfM photogrammetry as a tool in the capture of forensic footwear marks. This is applicable to photogrammetry freeware DigTrace but is equally relevant to other SfM solutions. SfM simply requires a digital camera, a scale bar, and a selection of oblique photographs of the trace in question taken at the scene. The output is a digital 3D point cloud of the surface and any plastic trace thereon. The first section of this paper examines the reliability of photogrammetry to capture the same data when repeatedly used on one impression, while the second part assesses the impact of varying cameras. Using cloud to cloud comparisons that measure the distance between two-point clouds we assess the variability between models. The results highlight how little variability is evident and therefore speak to the accuracy and consistency of such techniques in the capture of 3D traces. Using this method 3D footwear impressions can, in many substrates, be collected with a repeatability of 97% with any variation between models less than ~0.5mm.

3.4 Research Paper 3.4: Empirical evaluation of the reliability of photogrammetry software, in the recovery of 3D footwear impressions

See:

Larsen, H. J. and Bennett, M. R., 2020. Empirical Evaluation of the Reliability of Photogrammetry Software in the Recovery of Three-Dimensional Footwear Impressions. *Journal of Forensic Sciences*, 65 (5), 1722-1729.

https://eprints.bournemouth.ac.uk/34012/

3.5 Research Paper 3.5: Recovery via SfM photogrammetry of latent footprint impressions in carpet

Status: Manuscript accepted by Journal of Forensic Sciences on 17th March 2021. Scheduled to appear in July 2021 issue.

Contributions: The paper and associated experiments were conceived by Larsen during supervisory meetings with Bennett and Budka. The data was collected and analysed by Larsen. The text was drafted by Larsen with editorial input from Bennett and Budka.

Abstract

Impression evidence retained in carpet is usually recovered, if at all, in two dimensions via a vertical photograph. Here we show that recovery is also possible via SfM photogrammetry and this gives excellent results that allow digital measurements both in the x-y plane and by depth (z axis). This study focuses on recovery from polypropylene carpets which are widespread due to their resistance to wear and low cost. We show how traces can be recovered using both SfM photogrammetry and conventional photography with illumination provided via a crime scene light source. Experiments shows that traces are retained for considerable time periods if left undisturbed, in excess of four weeks, but are quickly lost in under 8 hours by subsequent footfall. A simple simulation shows how the movement of an individual can be determined from carpet traces and the value of 3D recovery is illustrated via a set of experiments conducted with barefoot traces. We draw attention to the fact that 3D models allow a more statistical-based approach to be taken to match bare footprints at crime scenes. SfM photogrammetry is shown to provide a useful compliment to existing techniques and therefore worthy of further experimentation and potentially operational use.

3.5 **Research Paper 3.5: Recovery via SfM photogrammetry of latent footprint impressions in carpet**

See:

Larsen, H.J., Budka, M. and Bennett, M. R., 2021. Recovery via SfM photogrammetry of latent footprint impressions in carpet. *Journal of Forensic Sciences*. (In Press).

https://eprints.bournemouth.ac.uk/35420/

3.6 Research Paper 3.6: Recovering of 3D footwear impressions from sandy substrates: technical note on the contribution of SfM photogrammetry

Status: Awaiting decision post revisions at Journal of Forensic Identification. Original manuscript submitted 1st September 2020.

Contributions: The paper and associated experiments were conceived by Larsen during supervisory meetings with Bennett and Budka. The data was collected and analysed by Larsen. The text was drafted by Larsen with editorial input from Bennett.

Abstract

Three-dimensional footwear impressions are often left at crime scenes, particularly in areas of dry sandy substrates common on footpaths, in roadside gutters and on waste ground. Loose fine sandy substrates can preserve remarkable levels of detail that can allow for the comparison of characteristics from wear and use of the shoe, beyond the consideration of class characteristics. A Crime Scene Investigator has a range of options at their disposal for the recovery of such an impression from casting through to 2D photography. Here we illustrate the use of SfM photogrammetry in the recovery of these sometimes 'difficult to cast' impressions. Our aim here is not to evaluate such methods in detail but simply draw the attention of CSIs to this potential. We do this via a series of different scenarios which illustrate the potential of SfM photogrammetry to provide a superior recovery method for sandy substrates. Given further evaluation and future evaluation of SfM methods we argue that it provides a potential complimentary recovery technique expanding the range of options available for loose, dry substrates.

3.6 **Research Paper 3.6: Recovering of 3D footwear impressions from sandy substrates: technical note on the contribution of SfM photogrammetry**

See:

Larsen, H. J. and Bennett, M., 2021. *Recovering of 3D footwear impressions from sandy substrates: technical note on the contribution of SfM photogrammetry*. Documentation. The Authors. (Unpublished).

https://eprints.bournemouth.ac.uk/35684/

3.7 Unpublished Technical Note 3.7: Use of contrast spray in the recovery via SfM photogrammetry of snow impressions.

Status: Unpublished technical note.

Contributions: The paper and associated experiments were conceived by Larsen during supervisory meetings with Bennett and Budka. The data was collected and analysed by Larsen. The text was drafted by Larsen with editorial input from Bennett and Budka.

Abstract

Effective recovery of 3D footwear impressions from snow covered areas has both huge potential and many challenges. Traditional recovery is either via casting, which is highly dependent on snow consistency, or via 2D photography with the associated challenge of established effective lighting. An alternative and complimentary recovery technique is to use SfM photogrammetry. This technical note explores the application of SfM in the recovery of footwear impressions left in snow identifying the challenges and potential. Use of a digital method has the additional benefit of allowing a range of digital analysis. This has been utilised in this example to provide a validation of the use of contrast or fixative sprays commonly used in the recovery of footwear impressions in snow. Using a comparison of point clouds generated through SfM photogrammetry, we have assessed the use of a contrast spray in its disturbance of an impression and whether it can increase the quality of digital outputs.

Introduction

Footwear impressions located on a snow- or ice-covered surface have both potential for data recovery and an associated risk with not harnessing that potential. Buck et al. (2006) and Bodziak (2017) discuss the data which can be obtained from snow impressions such as clues as to the approximate time of the crime, the number and direction of suspects, exit and entry points as well as information on the shoes themselves and potentially the wearer/owner. Buck et al. (2016) state that there is a good chance that impressions in snow retain fine details but that the difficulty has always been in collecting these details for identification purposes. The difficulty in collection has led to uncertainty in both the literature and in practice as to the true value of footwear impressions in snow. A point made by Bodziak (1999) who describes how the difficulty of using certain collection methods impacts on how often they are used in practice and as an excuse for not using them technicians may claim there is little value in the type of impression.

Casting is traditionally identified as the most appropriate way to collect impressions in snow (Buck et al. 2006; Battiest et al. 2016; Bodziak 2017; NPIA 2017). Casting, however, can provide many challenges especially, as noted by Hammer and Wolfe (2003) when there are multiple types of snow in existence that each need different treatment. Different casting materials are available for snow impressions such as gypsum, sulphur or dental stone. Each type of material has advantages and disadvantages but there is yet to be an ideal solution. The disadvantages of some of the different casting materials is their weight which is often enough to alter the impression from its original state (Bodziak 2017). Some dental stones and plaster involve exothermic reactions which also are problematic when dealing with snow. The NPIA (NPIA 2007) guidelines used in the UK currently advise that a snow print wax be used in certain circumstances to fix a snow impression.

There is a huge variety of different types of snow as the old aphorism about Inuit having over a hundred words for snow implies. Working with potential variety makes simple manual-based instructions difficult and most of the learning is experiential. As a result successful snow casting is based on experience and exposure to such traces. Therefore, as with most footwear recovery the default is to use a vertical 2D photograph, although Petraco et al. (2016) advocates the use of foam blocks (BioFoam^{TM}).

Optical laser scanning has been proposed as an alternative way of collecting 3D snow impressions and Buck et al. (2006) states that the technique is accurate as well as easy to use and mobile. It does however require an electrical current and investment in appropriate equipment. Refraction during scanning is also often a significant issue and not all scanners are suitable for capturing snow impressions (Bennett and Budka 2018). The application of SfM photogrammetry provides an alternative way of capturing a 3D snow impression. This has been explored in Paper-1 and the problems and challenges associated with applying SfM in snow are discussed there. The specific focus of this technical note is the use of contrast sprays as part of the SfM recovery process.

It is often necessary, depending on the type of snow an impression was made in, to assist in the visualisation of the impression details (Bodziak 2017). In environments where the snow is thick, reflective, with a bright light source and uniform in colour, additional contrast can improve the visualisation of both class and RAC characteristics. In Alaska the State Forensic Laboratory use a contrast spray when an impression is recovered by 2D photography. In the UK where the snow is usually much shallower and melts quickly to reveal patches of the subsurface it is unlikely to be necessary. The same technique however may have benefits for if an impression were to be recovered via SfM photogrammetry, but albeit in a different way. Increasing the textural variation within an impression may reduce the likelihood of holes, caused by uniformity.

The use of contrast spray as part of the SfM recovery process was tested in the UK to determine two factors (1) is the use of any spray, contrast or setting, disturbing the impression in any quantifiable way and (2) is the use of a contrast spray increasing the quality of an SfM model.

Method

Bournemouth and the surrounding area had two snow/frost episodes during the research period. One in March 2018 and again in February 2019. On both occasions' snow/frost impressions were collected. A brief secondment to the Alaskan State Forensic Laboratory in Anchorage hosted by David Kanaris, was also conducted to further understand the potential of SfM photogrammetry in a snow environment. The experiments reported here were however all based in the UK.

A snow impression was created using a Nike trainer; the volunteer (weighing 60kg) creating a dynamic impression by walking through an area of snow. A scale was placed next to the impression and photographed for SfM photogrammetry using the standard collection protocol. The impression was then lightly dusted with a dark grey matte spray paint. SfM recovery was then repeated as before. Both models were built in DigTrace using its embedded OpenMVG SfM engine. They were then auto rectified, cropped and scaled within DigTrace. The models were then saved as PLY files and imported into CloudCompare where the digital comparison was undertaken. A comparison test was performed as detailed in section 2.2.1.

Results

The results show a mean distance between the two clouds at 0.509 mm and a standard deviation of 0.412 mm (Figure 45).

Upon visual analysis of Model A (without spray) and Model B (with spray), the model having had spray applied was of higher overall quality, this is determined by the presence of fewer holes and increased visualisation of features. Figure 45 shows the comparison output displayed as a scalar field. Which shows little difference in the two models and highlighting little disturbance created by the spray. The more uniform the colour in Figure 45 (blue = 0 to <3 mm) the closer the two clouds map are one to the other. If the spray had greatly disturbed elements of the substrate, this would be apparent in this comparison with increased red areas.

An insight into the point cloud coverage was also produced using a quality assurance method as described in Paper 3. Column one (Figure 46) shows the point cloud coverage where an even colour shows a more even spread of points. A more even coverage can be seen in the sprayed impression, most notably, in the outskirts of the impression. The left hand set of histograms (Figure 46) shows the point frequency throughout the model (grid interval 0.5mm), with the sprayed impression resulting in a higher number of units with a higher point frequency than the non-sprayed impression. To put another way, in the sprayed version there are fewer areas of low-density point coverage.

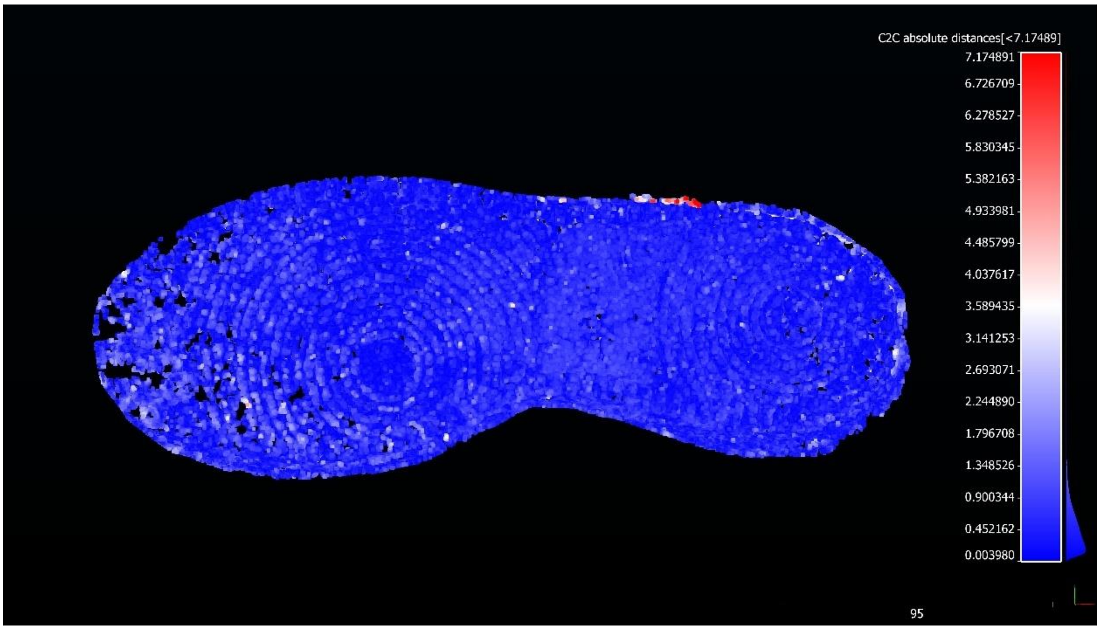
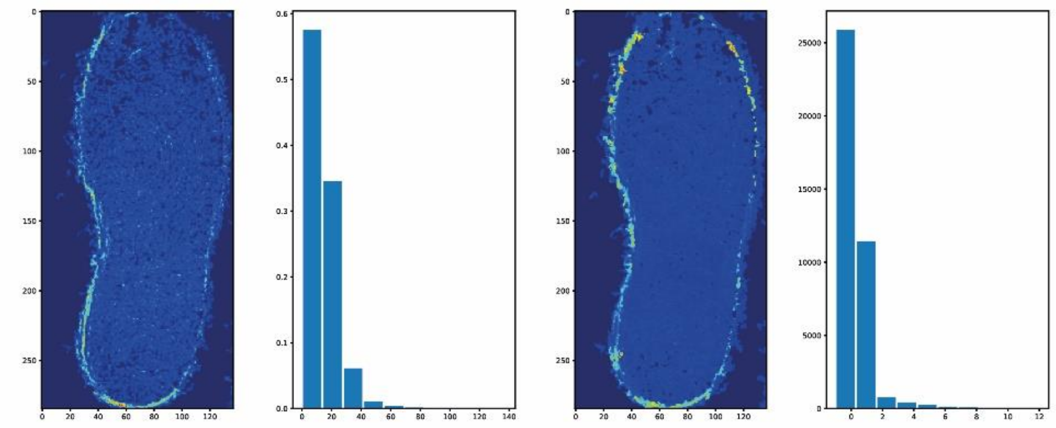
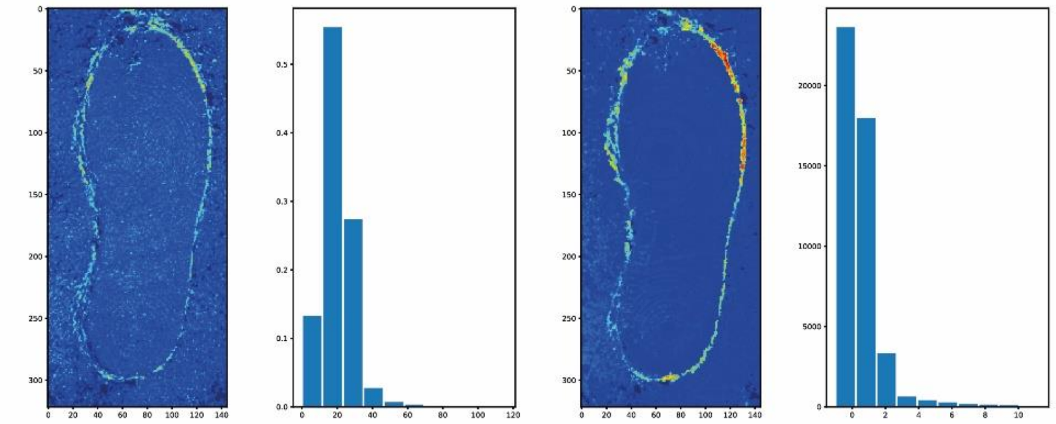


Figure 45. Comparison output of one snow model with contrast spray and one without. Displayed in Scalar field. Scale in mm.



A. Without Spray



B. With Spray

Figure 46. Quality Assurance Model output. Row A: Point Cloud distribution from a snow impression without contrast spray applied. Row B: Point Cloud distribution from a snow impression with contrast spray applied.

Discussion/Conclusion

To fully assess the extent to which a spray may alter a snow footwear impression, this study would need to be replicated multiple times. This is recognised as a limitation of the study. However, while limited in scope and data, this experiment suggests that the application of spray paint in this instance did not damage or alter the impression in a way that could compromise the analysis of the impression. Moreover the results also indicate that a contrast spray will improve the density of points within the SfM model and therefore the overall quality with which a snow footwear impression will be recovered. This point requires more extensive testing before general advice with respect to the use of a contrast spray can be provided. It does however indicate that if a spray is used to enhance a 2D photograph it should not preclude the additional and complimentary capture via SfM Photogrammetry. The results are only applicable to one type of snow, in one type of environment and guidance should therefore be sought from the small library of other literature discussing this issue (Bodziak and Hammer 2006; Battiest et al. 2016; Bodziak 2017; Sabolich 2018). This should be further explored before any operational use of SfM photogrammetry for snow recovery. A key advantage of SfM is the flexibility in when it can be deployed. Spraying and photographing a model after initial crime scene photography would not cause any undue disturbance before the primary evidence collection (2D photography) method was used.

3.8 Chapter conclusion

This chapter provides a broad insight into the use of SfM photogrammetry for the recovery of 3D impressions evidence. To conclude the chapter, highlights have been created, in much a similar way as is now standard for published research articles. These are the key contributions of the chapter and those with the highest level of potential impact. Table 25 goes on to summarise the contributions of the chapter with regard to how specific papers address each of the research questions.

Highlights:

One: Protocol for determining precision set out that can be used by any practitioner.

Two: A range of examples and cases studies are presented highlighting applicability to forensic context (Mock crime scene examples can be found in appendices I,II and III)

Three: Future research agenda to aid application in practice is established.

Four: SfM photogrammetry is a complimentary recovery method for 3D impressions in carpet

Five: Undisturbed polypropylene carpet impressions can remain for over a month

Six: Statistical approaches to analysis of barefoot impressions can compliment expert opinion

Paper:	Addressing research question(s):
3.1	**One: Is the use of SfM photogrammetry as a 3D footwear impression recovery tool scientifically valid? This is defined using the President's Council of Advisors on Science and Technology (PCAST) report (2016) which discusses the key points of foundational validity to include reliability, reproducibility, repeatability, accuracy, and consistency.** **Two: Is the use of SfM photogrammetry scientifically valid in the range of environments in which 3D footwear evidence is typically found in a country such as the United Kingdom (UK)?** Elements of scientific validity of SfM recovery are easily obtainable as demonstrated in Paper 3.1. A set of standards are achieved via a model to determine precision and instructions for determining accuracy are laid out. This addresses questions of repeatability and reproducibility of which in general, are high, but can be lowered through the various elements that equate to accuracy and precision in this context. An important note here is that further analysis can be easily undertaken if requirements of a particular audience are not yet met. Paper 3.1 addresses the use of SfM across environments, the precision model allows for environment to sit, as it should, as an important element that can contribute to a methods precision and rate of error. The results of this study can drive future research into the methods which show the highest rates of potential error, such as snow or impressions in wet substrates.
3.2	**One: Is the use of SfM photogrammetry as a 3D footwear impression recovery tool scientifically valid? This is defined using the President's Council of Advisors on Science and Technology (PCAST) report (2016) which discusses the key points of foundational validity to include reliability, reproducibility, repeatability, accuracy, and consistency.** Paper 3.2 addresses the software used in this research and contributes to the answering of Research Question One. Whilst not addressing the scientific foundation of SfM photogrammetry directly, it addresses an element affecting accuracy of the method as laid out in the accuracy equation in Paper 3.1. A = (Eq, P, S, O, E, T) Where S = software. It is the authors opinion, through investigation in Paper 3.2, that SfM software DigTrace and by extension other similar freeware, can build models to an appropriate standard for forensic evidence; eliminating the need for expensive commercial software NS (not significant) thereby making it a

	viable option for a budget conscious audience. Literature from other communities (e.g. ichnology, archaeology, palaeontology) support this recommendation
3.3	**One: Is the use of SfM photogrammetry as a 3D footwear impression recovery tool scientifically valid? This is defined using the President's Council of Advisors on Science and Technology (PCAST) report (2016) which discusses the key points of foundational validity to include reliability, reproducibility, repeatability, accuracy, and consistency.** **Two: Is the use of SfM photogrammetry scientifically valid in the range of environments in which 3D footwear evidence is typically found in a country a such as the United Kingdom (UK)?** **Three: What are the practical advantages of SfM photogrammetry when measured against current methods and practice?** Paper 3.3 is comprised of multiple elements contributing to the scientific foundation of SfM. With contextually relevant examples. Also addressed are the logistical advantages and disadvantages of SfM. Notable points are the minimal requirements of resources to engage in all stages of SfM. Recovery does not require masses of equipment, modern phones have sufficient cameras, and analysis options are wide using freeware.
3.4	**One: Is the use of SfM photogrammetry as a 3D footwear impression recovery tool scientifically valid? This is defined using the President's Council of Advisors on Science and Technology (PCAST) report (2016) which discusses the key points of foundational validity to include reliability, reproducibility, repeatability, accuracy, and consistency.** **Two: Is the use of SfM photogrammetry scientifically valid in the range of environments in which 3D footwear evidence is typically found in a country a such as the United Kingdom (UK)?** Paper 3.4 further addresses overall reliability of SfM in the recovery of 3D impressions in the substrates of snow, sand and soil. This secondary test of repeatability using cloud comparison methods shows the use of SfM to have high levels of repeatability in sand, slightest lower in soil, and lower again in snow. This paper also focuses on providing repeatability scores when impressions are recovered with different cameras, little to no disparity in models can be seen when comparing a high quality DLSR against an iPhone camera.
3.5	**Two: Is the use of SfM photogrammetry scientifically valid in the range of environments in which 3D footwear evidence is typically found in a country a such as the United Kingdom (UK)?** **Seven: How can areas of 3D footwear recovery that are often overlooked, have their value increased through the use of SfM?**

	Eight: Can the introduction of digital recovery also introduce statistical reporting that satisfies both traditionalist approaches and Bayesian approaches? Paper 3.5 reports results relevant to multiple research questions and is comprised of some of the most impactful aspects of this research. There is no literature available detailing a method that can successfully recover a carpet impression, digitally or otherwise in all three dimensions. This paper is therefore the first of its kind in allowing the forensic community to understand the value of carpet impressions and providing them a method in which they can recover them. Multiple personal communications have highlighted carpet as a medium 3D impressions are found, but it is clear that they are only ever recovered in 2D. Paper 3.5 also highlights methods in which statistical analysis can assist an expert examiner, it is hoped that examples of use such as this will inspire examiners to incorporate these methods in their reporting going forward.
3.6	**Two: Is the use of SfM photogrammetry scientifically valid in the range of environments in which 3D footwear evidence is typically found in a country a such as the United Kingdom (UK)?** **Seven: How can areas of 3D footwear recovery that are often overlooked, have their value increased through the use of SfM?** Paper 3.6 specifically looks at the recovery of ‘difficult to cast’ impressions such as those in loose sand substrates. The complimentary use of SfM alongside traditional methods has the potential to have the most impact for these types of impressions.
3.7	**One: Is the use of SfM photogrammetry as a 3D footwear impression recovery tool scientifically valid? This is defined using the President’s Council of Advisors on Science and Technology (PCAST) report (2016) which discusses the key points of foundational validity to include reliability, reproducibility, repeatability, accuracy, and consistency.** **Two: Is the use of SfM photogrammetry scientifically valid in the range of environments in which 3D footwear evidence is typically found in a country a such as the United Kingdom (UK)?** Paper 3.7 illustrates that caution should be taken when using SfM as a recovery method in snow. As part of addressing research questions 1 and 2, understanding the full extent of the methods limitations in snow is key and recommendations to improve the accuracy of recovery in snow have been made where possible. There is an element similar to casting here; you only realise a model has failed, or not picked up the required detail, when you return to the lab. In order to overcome this issue, traditional methods can be used in conjunction with SfM or multiple SfM models can be taken to increase chances of

	obtaining a successful model. Transparent reporting of potential error in snow models and utilising all methods at an examiners disposal should allow for the use of SfM in this substrate, should there be gain to be had.

Table 25. Research questions (Table 1) addressed in chapter three.

Chapter four: Traditional methods of recovery and the inclusion of a digital approach

The previous chapter established much of the scientific validity of SfM photogrammetry as a stand-alone technique. Making little comparisons to traditional methods, work in Chapter 3 focuses on the use of SfM in a relatively simple context.

	Paper Title	Research Questions Addressed
4.1	Investigation into the repeatability and precision of casting 3D impressions	5
4.2	Recovery of 3D footwear impressions using a range of different techniques	1,2,3,4

Table 26. Contents of chapter four addressing specific research questions (Table 1)

In this chapter, other recovery methods are considered as their relevance is unquestionable. It is recognised that in order for a new technique to replace another, operationally heavy comparisons need to be made, including the use of trained recovery experts undertaking data collection. As direct method replacement is not the intended aim of this research, comparative experiments are limited and are contextualised around showing benefits and limitations of multiple techniques alongside one another and highlighting how conjunctive use can strengthen each method. In the length of this research, the author has made in the region of 50-100 casts and a similar number of crime scene quality photographs have been produced and in doing so has developed a level of experience that, whilst not rivalling a professional examiner, has allowed for simple comparative exercises to be undertaken.

The use of digital recovery over traditional methods also increases the use of digital analysis. Producing statistically based analysis is far simpler with a digital recovery method vs a physical cast or a 2D photograph. The introduction of these digital methods does, however, allow us to go back to dated methods such as casting and shine a light on the scientific validity that is currently lacking. Chapter 4 (Table 26) begins with an example of this concept and applies techniques ordinarily associated with 3D digital data to physical casts (Paper 4.1).

Following this and concluding Chapter 4 is Paper 4.2, this is the closest to a comparative exercise as will be seen in this thesis. A key feature that is highlighted throughout Chapter 3 is the increased visualisation options available with SfM photogrammetry and further examination of this was critical in achieving aim 4. Do the outputs of SfM photogrammetry produce superior visualisation of impression features when assessed next to examples of current methods? The use of casting and photography in this paper are considered on a ‘basic level’ therefore no extensive use of lighting was used to help aid the methods, which may have changed the results. There is little way of quantifying the levels a CSI will go to in enhancing the visualisation of features and no understanding of how consistently this is done throughout the country. The paper should therefore not be considered evidence for the replacement of one technique with another based on a better rate of visualisation.

4.1 Research Paper 4.1: Investigation into the repeatability and precision of casting 3D impressions

Status: Intended submission 2021.

Contributions: The paper and associated experiments were conceived by Larsen during supervisory meetings with Bennett and Budka. The data was collected and analysed by Larsen. The text was drafted by Larsen with editorial input from Bennett and Budka.

Abstract

The procedure of casting of 3D footwear impressions found at crime scenes has been in place since the early 1900s. For many CSI’s casting is often considered to be the gold standard for recovery, despite little or no research to validate the method in terms of reliability, repeatability and accuracy. In the UK casting has fallen out of favour except in the most important cases due to the time it takes and improvements in conventional forensic photography. It is, however, still widely used in other countries. With the increasing availability of digital alternatives for 3D recovery such as the use of optical laser scanning or SfM photogrammetry it is perhaps timely to consider the potential errors around casting. Using a dataset of 20 casts all created from one flexible silicon mould, two separate assessments are used to examine the variability between each of the casts to determine an estimate of precision.

4.1 **Research Paper 4.1: Investigation into the repeatability and precision of casting 3D impressions**

See:

Larsen, H. J. and Bennett, M., 2021. *Investigation into the repeatability and precision of casting 3D impressions*. Documentation. The Authors. (Unpublished)

https://eprints.bournemouth.ac.uk/35685/

4.2 **Research Paper 4.2: Recovery of 3D footwear impressions using a range of different techniques**

Status: Accepted for publication in Journal of Forensic Sciences (JFS) on 16th December 2020. Appearing in May 2021 issue.

Contributions: The paper and associated experiments were conceived by Larsen during supervisory meetings with Bennett and Budka. The data was collected and analysed by Larsen. The text was drafted by Larsen with editorial input from Bennett and Budka.

Abstract

3D 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 2D photography with SfM photogrammetry. We focus both on the recovery of class characteristics (sole pattern) and RACs caused by damage. We examine how different recovery techniques influence visualisation of outsole features and discuss what effect this may have on evidential value. Five shoes and their associated 3D 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 visualisation of both class and RACs, giving a better definition in detail in some instances. The use of SfM as a complimentary approach can therefore lead to a potential increase in evidential value.

4.2 **Research Paper 4.2: Recovery of 3D footwear impressions using a range of different techniques**

See:

Larsen, H.J. and Bennett, M. R., 2021. Recovery of 3D footwear impressions using a range of different techniques. *Journal of Forensic Sciences*, 66 (3), 1056-1064.

https://eprints.bournemouth.ac.uk/35035/

4.3 Chapter conclusion

This chapter provides critical work required on current recovery methods as well as introducing SfM into the range of methods currently used. Highlights have been used here to isolate the key contributions of the chapter alongside Table 35, which further clarifies the relevance of this chapter to the research questions and aims.

Highlights:

One: SfM recovery compares favourably over other methods when visualising RACs.

Two: Key advantages of SfM are the use of depth colour renders and comparison features within SfM software (examples of this in a crime scene context can be found in appendices I, II and III)

Three: Digital recovery allows superior visualisation, digital file sharing and searching.

Four: Casting repeatability shows high levels of precision

Paper:	Addressing research question
4.1	**Five. What is the measure of repeatability for currently used footwear recovery methods, specifically casting?** A measure of repeatability has been accomplished in Paper 4.1 and shows there to be a high level of precision in the method of casting. These results, whilst the first of their kind are, however, not without limitations due to the nature of the method. Measuring repeatability of a destructive method is invariably going to pose a challenge. There are numerous variables to consider when investigating the accuracy in repeated use of a recovery method. In this instance these include many subtle differences that may occur as a result of the weight of the casting material, the manner in which they have been prepared, the manner in which they have been applied to the impression and so on. Paper 4.1 highlights some variability in the recovery of RACs when one impression with a significant RAC was repeatably cast. Should this be as a result of the subtle variables at play is cause for further research. Casting has been accepted by the community as the most appropriate way to recover 3D impression evidence but on little scientific merit. The contribution of Paper 4.1 introduces the first attempt to provide this in a scientific manner and not based on examiner experiences/testimony. This contribution provides a portion of the necessary scientific foundation for casting, but a question remains as to whether casting can ever truly be, as determined by appropriate statistical testing, scientifically valid.
4.2	**Four. Do the outputs of SfM photogrammetry produce superior visualisation of impression features when assessed next to examples of current methods?** Paper 4.2 addresses this question with respect to both class and RACs. Superior visualisation can be seen in some instances of SfM use and more than anything, this work provides a great basis for future research. The ease in which comparisons can be undertaken have been demonstrated, although the next step, if one is to replace an existing method with SfM, requires a more formal comparison undertaken by forensic professionals. For the purpose of this research and addressing the above question, SfM can provide superior visualisation and should, off the back of Paper 4.2 be confidently used as a complimentary technique.

Table 35. Research questions (Table 1) addressed in chapter four.

Chapter five: Discussion

The data in this thesis broadly assesses the use of SfM photogrammetry for the specific application of the recovery of forensic footwear impressions. Three main themes have emerged during this research, that highlight the main areas of impact. The main theme is the clear viability of the method for its intended purpose. This leads to the question of whether the research equates to the scientific foundation required in order for the technique to be operationally deployable.

The second theme is the positioning of the technique in amongst the current recovery methods and the assessment of how SfM photogrammetry could exist in an operational setting alongside more traditional practice. Finally, the third theme focuses around the potential trajectory of SfM photogrammetry, from its evolution elsewhere, to its potential use by the forensic community.

Theme 1 – Viability of SfM Photogrammetry as a recovery tool for 3D footwear impressions.

The central aim of this thesis was to establish a body of research to support the use of SfM photogrammetry in the recovery of 3D footwear impressions. The PCAST (2016) report proposes criteria and requirements against which the research can be measured. The report states (p47), 'For a metrological[34] method to be scientifically valid and reliable, the procedures that comprise it must be shown, based on empirical studies, to be repeatable, reproducible, and accurate, at levels that have been measured and are appropriate to the intended application'. Using these broad criteria, we can discuss the degree to which the application of SfM to forensic footwear meets these criteria.

Repeatability measures the degree to which a method will produce the same results time after time REFs?. Paper 3.1 and further discussed in Paper 3.3, sets out the potential sources of error associated with SfM footwear recovery. In this study 30-50 separate models were created via SfM photogrammetry of

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[34] **Metrology** *is the scientific study of measurement*.

the same footwear impression. This was completed for footwear impressions across a range of substrates and gives an idea of the technique's overall precision (Table 13). Precision estimates were provided for individual environments in Paper 3.1 and we can average (mean) four of these (Sand, Mud1, Mud2, Concrete Control; Table 13) completed by one user, protocol and camera to give an overall estimate of the technique's precision, namely ±0.282mm. This high level of precision level is promising, and to some degree satisfies the requirement that the method should be repeatable. It is, however, slightly misleading because specific environmental conditions associated with a specific trace come into play. For example, the error rate for a standard mud impression may be quite low (Table 13), but if saturated and containing standing water the precision may fall quite dramatically. The method established in Paper 3.1 and further utilised in Papers 3.3 and 4.1, establishes a way for a practitioner to accredit their own application of the SfM method and in theory accompany each piece of evidence 'outside the norm' with a specific precision estimate. Further work on repeatability can be seen in Paper 3.4 showing, using point cloud comparisons, the differences in individual models of the same impression. As can be expected, higher repeatability is found in some environments over others. In sand and mud a mean distance between points in any 2 clouds is ~±0.2mm with a standard error of ~±0.01mm, snow shows higher differences of ±0.5mm. All likely variability between repeated use of SfM by one user is very low. It is significantly harder to produce these types of experiments for traditional methods such as casting meaning little comparative work can be done to provide evidence that one method's repeatability is superior to another.

Reproducibility refers to multiple users obtaining the same results. It also seems equally relevant to other singular changes in variables, such as obtaining the same results using different input sources (which is the camera used to obtain the photographs in this instance). The preliminary analysis undertaken suggests that variance caused by the operator is relatively small as indicated by the precision scores in Table 13 (Paper 3.1) and as further discussed in Paper 3.3. The photographs taken have to be extremely poor before this becomes a real issue. As long as the operator takes sufficient photographs from different positions the technique is forgiving and good models will be built. A set of ten volunteer undergraduate forensic students were given basic guidance on the practice of photographing an impression for photogrammetry (training lasting around 60 mins). Identifiable user issues such as the size of the area needing to be photographed were quickly identified during this time and rectified with further guidance. Experience and practice as with any forensic technique is beneficial especially when dealing with more challenging substrates such as snow (Paper 3.7). Whilst the use of SfM does not completely eradicate the need for experienced examiners, and whilst a subjective claim, it is likely it will reduce the need. Additionally, it is much easier to gain experience with a technique that does not take much time or resources, with examiners being able to practice with no associated cost. Experience of this technique would be very quick to build should operational results show any large disparities in user variance.

Further work is, however, needed in order to provide statistical confirmation of the inter-operator reliability and it would be logical to follow the methods set out by Reel et al. (2010) and widely followed in medical trials (e.g., Ukoumunne et al. 2002; Ukoumunne et al. 2003; Pellis et al. 2003; Bobak et al. 2018). Using ICC reliability testing, a value of the variance could be provided to the forensic community.

The equipment used may also impact the reproducibility of recovery. Paper 3.4 provides a first order estimate of the potential impact of different cameras (±0.193mm) in all three dimensions, the x, y and z planes. It is likely that a crime scene quality camera is always going to be available in the UK, but this is not always the case in other areas of the world. These restrictions should be more openly discussed in the literature and considered when assessing the scientific validity of recovery methods.

Paper 3.3 addresses accuracy in SfM with respect to the four areas of error which have been attributed to the context of footwear recovery. In the context of large-scale architectural modelling using SfM, Napolitano and Glisic, (2018) illustrates some of the factors influencing accuracy (Figure 54).

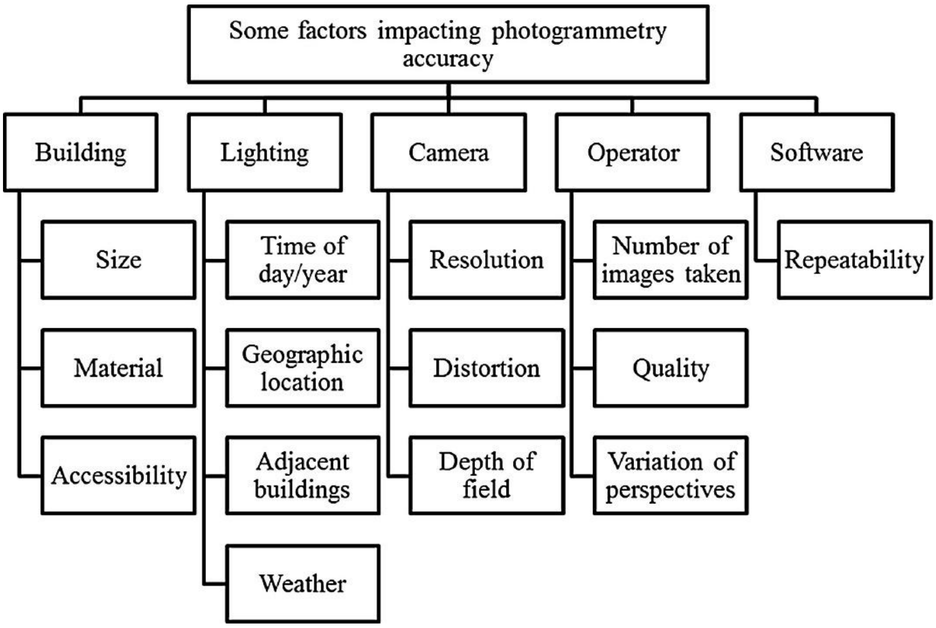

Figure 54. (Napolitano and Glisic 2018) Factors impacting photogrammetry accuracy. Relevant to a large scale photogrammetry project.

We can use this simple illustration to assess which areas of accuracy are most relevant to the application within forensic footwear and review if this research has satisfied those factors. Building factors do not need to be considered but this factor is equivalent to environmental factors. The accessibility of a trace for example, should it be covered by foliage or surrounded by a lot of overhanging vegetation, could impact an examiner's ability to take photos equating to an accurate model. Lighting, whilst a relevant factor, can be mitigated well in respect to recovering a footwear impression. Adding an additional lighting source to visualise the outline and textures of an impression is a simple task and the equipment required for this is standard within a crime scene examiners' kit. One element of lighting that is of high importance is the appropriate camera settings ensuring the colour textures of the model are nicely brought forward. This will increase the overall quality of the consequent model. An example of how an unlit photo can reduce the textural variation of the photo can be seen in Paper 3.6 in Figure 38 and a further example of the differences lighting can have on a model can be seen in Paper 3.4, Figure 27. Many of the factors already discussed under reproducibility are relevant here such as operator experience/training, equipment used. The software factor is largely alleviated in this instance as repeatability issues are often faced on large sites. The software utilised in this research has been subject to a comparison against leading commercial software and this can, to some degree, attest to levels of software accuracy (Paper 3.2). Similar methodologies have been used to understand accuracy and quality in SfM. Koutsoudis et al. (2013) performed a cloud to mesh comparison of a laser scan and an SfM photogrammetry model to determine an element of accuracy based on the ground truth of the laser scan. They determined that the number of input images used was crucial to the best reconstruction results and that feature richness of a surface also contributes to the accuracy of image-based reconstruction. Can you critique this paper further?

Accuracy in photogrammetry is an active research field and it can be inferred from such a wide landscape of papers (e.g., Falkingham 2012; James and Robson 2012; Jalandoni et al. 2018) that the levels of accuracy are appropriate for scientific use relative to 'gold standard' methods such as laser scanning (Bennett et al. 2013; Charbonnier et al. 2013). Correct scaling of a model and the application of a calibration test can lead to model accuracy being easily determinable throughout a forensic investigation. As discussed in Paper 3.1 and in further detail in Paper 3.3, determining levels of accuracy on an x, y and z plane are achievable with relative ease. The use of Lego™ bricks to 'calibrate' accuracy for a given user, equipment and environment allows accuracy to be continually proven per piece of evidence if required.The ability to confirm accuracy at multiple stages of the evidential chain, by simply measuring the scale in the model to confirm real world dimensions, is a very useful feature.

The application of determining accuracy and precision using the method in Paper 3.1, is particularly advantageous due to the methods ability to be applied to an individual practitioner, to determine their own levels of precision/reproducibility. Instead of providing a potentially misleading universal value for the accuracy and precision of SfM in this context, a method with far greater sensitivity has been provided. Providing details of this method allows us to move away from universal statements of validity often used in a forensic context. This method is specific to a particular recovery and in line with an accredited approach.

The importance of accreditation is of huge relevance to modern day forensic science and certainly not an aspect lost on those in the community. In 2007, the role of the forensic science regulator was introduced, to tackle the "irremediable problems with the quality of scientific evidence in the UK" (McCartney and Amoako 2017, p945). Over a decade later however, gaps in regulation and accreditation are still seen (McCartney and Amoako 2017) and regularly highlighted (NRC 2009; PCAST 2016; Tully 2020). These generally include statements regarding a lack of scientific validity of techniques and "widespread failures to disclose limitations and uncertainties in reports" (McCartney and Amoako 2017, p946). Such testaments show how highly transparent error rate projections similar to that presented in Paper 3.1, are absolutely needed, and remain crucial to the forward progression of forensic science.

In choosing a methodology for this research, the notion of providing evidence of the methods competency in environments appropriate to the intended application was a fundamental requirement and can essentially be partitioned into two points. One point addresses the ultimate question of whether the levels of accuracy and precision that can be obtained by a typical user are fit for purpose. Specifically, are they able to visualise the features of a footwear impression. The second point addresses the logistical applicability of this method for operational use. Together these points can steer the research into alignment with aspects of operational practice.

To understand if this method is accurate and precise enough to successfully recover footwear evidence requires us to return to the types of feature commonly found in footwear evidence, evidence of which can be seen in Paper 3.5 in the medium of carpet. Both class, wear and RACs are visualised using SfM photogrammetry both on par and in some instances, superior to, the recovery via 2D photography plus the use of oblique lighting. The size of features varies in these examples and the smallest is a matter of millimetres. A further example is in Paper 4.2 which offers visualisation of both class and RACs in SfM models alongside the visualisation seen in casting and 2D photography. Whilst it is difficult to provide a definitive size of feature that SfM photogrammetry can consistently recover, due to such vast variables, it is in comparison with current methods that we can offer assurance that the technique is fit for purpose.

Given the large number of substrates in which 3D impressions can be found, applying a simple quality score to each of the environments tested, further illustrates the methods ability to be fit for purpose (Table 36).

On approaching this research multiple efforts were made to gain data from forensic services that could provide a list of environments in which 3D footwear impressions are commonly, and not so commonly found. Unfortunately, and interestingly, these are never documented digitally. A footwear analysis report from Bedfordshire police is the closest quantitative data obtained. Separated by ‘Surface Type’ as per Exhibit records, this report simply shows the number of casts submitted as evidence in a year. It shows in 2017 65 casts were submitted as exhibits, with 3 being attributed to soil/mud, 1 attributed to a door and the rest simply labelled under ‘cast’. This is the extent to which 3D footwear impression evidence is documented. There are, however, many 2D surfaces which are noted. Information regarding the medium the casts were made in, it seems, is being left in the crime scene examiners handwritten notes or an inference from accompanying photographs. It was therefore an effort of personal communication to ascertain frequent mediums in which to test SfM photogrammetry. Tables 5, 6 and 7 in Section 1.3.4 detail these communications and Table 36 shows the response from this research. A broad interpretation of this table shows how texture can play a large part in securing the highest quality SfM models. Sand and modelling compounds such as Bubber^{TM} exhibit very high-quality results due to the fine nature of their grains, providing identifiable pixels for the software to detect. It is also abundantly clear that snow is particularly challenging. Further investigations into snow recovery (Paper 3.7) show quality issues can be mitigated to a degree but much further work is required to establish a way of consistently achieving high results. It should be noted here that the use of a digital method allows work to go ahead. Research into casting in snow dates back to as early as 1984 and can be seen as recently as 2016, it is a relatively, highly researched area due to the difficulties involved. We are, however, at a stage where it is likely to be as good as it is ever going to be without the introduction of a completely new casting material. That cannot be said about photogrammetry, which provides wide scope for improvement and is in a very active field of research doing just that. Regardless of community, if improvements are made in one discipline, those advancements can then be easily brought across to the forensic application of photogrammetry. For example, White Sands National park sees many of the same challenges as snow, such as uniformity of colour, texture and bright lights causing reflections.

To address the second point of purely logistical applicability, we can look at where earlier research into digital recovery of 3D impressions has fallen. Many proposed digital 3D recovery techniques have required equipment requiring a power source, or a budget far outside that of UK police (e.g., Komar et al. 2012; Gamage et al. 2013). A key part of providing the forensic community with an operationally deployable tool is the accompanying confidence that it will work in a variety of circumstances that are quite literally, in some cases, stumbled across. Meaning the practicality of the method is just as important as the ability to successfully recover impression features. The logistical properties of SfM photogrammetry can be found in Table 19 alongside those of current and proposed methods for 3D impression recovery.

Having assessed the above criteria, the foundations of scientific validity are in place. Through a combination of established validity and validity testing specific to a forensic application, this is considered the minimum required for the technique to be operationally deployable. There is a lot of further research that can be undertaken to find new and innovative ways of analysing 3D point clouds to gain all there is to know from the data and the behavioural inferences we can gain from footwear evidence. This is particularly relevant to intelligence led policing as well as increasing overall evidence value. If any aspect of the technique should fall to a standard that practitioners are not happy with, there should be confidence in the community that resolutions are possible. This research alone aims to provide some of that confidence illustrating the array of methods and statistical analysis available when incorporating digital recovery into a forensic realm.

		Specific Features of Recovery - Subject to SfM output quality and original impression quality				
Environment	Overall quality score: Application of SfM to the recovery of footwear impressions in this substrate: User Opinion	Visibility of Class Characteristics	Visibility of Wear Characteristics	Visibility of RACs	Model Quality	Model Quality: Consistency with repeated use
Light Snow UK	Medium	High	Low	Medium	Medium	Medium
Heavy Snow Alaska	Low	Medium	Low	Medium	Low	Low
Heavy Snow Italy	Medium	High	Low	Medium	Medium	Medium
Frost UK	High	High	Medium	Medium	High	High
Beach Sand (Dry)	High	High	Medium	High	High	High
Beach Sand (Wet)	High	High	High	High	High	High
Playground Sand (Dry	High	High	Medium	High	High	High
Builders Sand (Dry)	High	High	Medium	High	High	High
Builders Sand (Wet)	High	High	High	High	High	High
Wet Soil (Clay)	Medium	High	Medium	High	Medium	High
Wet Soil (not clay)	Medium	Medium	Medium	Medium	Medium	Medium
Clay Soil (Dry)	High	High	High	High	High	High
Clay Soil (Wet)	Medium	High	Medium	Medium	Medium	Medium
Stony Sand	High	High	High	High	High	High

Spilt food goods: Flour	High	High	Low	Medium	High	High
Cardboard	Low	Low	Low	Low	Low	Low
Paper Towel	Low	Low	Loe	Low	Medium	Medium
Bread	High	High	High	High	High	High
Polypropelene Carpet (Low Wear)	Medium	High	Medium	Medium	High	Medium
Polypropelene Carpet (Medium Wear)	Medium	High	Medium	Medium	High	Medium
Polypropelene Carpet (High Wear)	Medium	High	Medium	Medium	High	Medium
Modelling Compound: Bubber^{TM}	High	High	High	High	High	High
Salt Dough	High	High	High	High	High	High
PlayDough	High	High	High	High	High	High
			Other			
3D Fingerprints	High: Visualisation of ridge detail					
Tyre Tracks	High					
Writing Analysis	Medium: Depth analysis available					

* User opinion based on: Even and high point cloud coverage; Few holes in model; Colours and textures of original surface well translated in model.

Table 36. Quality scores assigned to all substrates recovered via SfM throughout this project. Based on author opinion.

Theme 2 – Illustrating the value of SfM photogrammetry with respect to existing methods

In order for a new technique to gain traction in forensic practice a degree of advocacy is potentially required. At an objective level this is about the comparative accuracy and potential of two different recovery techniques, but it also has an emotional element since changing traditional entrenched practice, even when the advantages are clear, can be difficult. Personal communications from members of the vertebrate ichnology community[35] have attested to such issues in a similar context, with an older generation preferring to produce hand drawn sketches of tracks over the use of digital 3D recovery.

The data presented in Table 13 and discussed in Papers 3.1 and 3.3 suggests that the accuracy of SfM based recovery is equivalent to if not slightly better than other techniques. Like any technique its accuracy varies with the environment in which it is deployed and by the practitioner's competence.

The reviewer reaction to some of the papers submitted provides insight into this challenge (Table 37). One of the issues raised is to challenge the degree to which there is a 'level field'. Several traditional examiners believe they could have taken better crime scene photographs, which is undoubtedly true, and that if they had, the advantages of SfM would be negligible. Others have demanded community wide trials (Table 37). The issue as they see it is an either-or situation, rather than something more subtle and complimentary. SfM in conjunction with other techniques allows one to perform analyses that would not be possible. The key complimentary advantage is the ability of SfM to allow depth to be measured, theoretically possible from a cast but rarely done, especially in dealing with something as subtle as the degree of heel wear. Visualizing depth via different colour-depth renders is a clear advantage as illustrated in several of the papers (Paper 3.3; Figure 20; Figure 21; Paper 3.6).

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[35] Professor Matthew Bennett – Environmental and geographical sciences
Dr Matteo Belvedere – Earth Sciences
Dr Ashleigh Wiseman – Evolutionary Biomechanics

	Reviewer Comment	Response/Evidence of?
1	The paper should focus on SfM more than bashing casting and photography.	An emotive comment highlighting just how strong attachment is to a technique. No un-evidenced claims or comments were made with respect to casting to elicit this response. It would appear the reviewer took any fair criticism of casting *personally*.
2	The author seems insistent on criticizing casting. Absolutely anything can be cast and cast successfully, including soft fragile soles, wet muddy soils, all type of snow, and even indented writing from paper	This is a strong claim, and to deem a cast successful is a subjective view. Several scientific papers address issues with casting (e.g., Buck et al. 2007; Sabolich 2018).
3	Failures with casting are attributed to a lack of having the proper materials to cast with, and or a lack of training or experience.	Whilst both valid points, it can be argued that there is more to casting failures than just lack of materials or training. Many of which are highlighted in published works (e.g., Buck et al. 2007; Sabolich 2018).
4	Silicone was never a good method and is never used. Why even mention it?	UK NPIA guidelines discuss silicone as a lesser-known casting material, but suggest its properties are appropriate nonetheless. The reviewer provides no scientific evidence to this claim.
5	It is a constant battle to try and encourage the use of casting for police departments because they may have limited resources; but to see a paper like this to state the casting process will not work is mis-informing the reader and inferring that casting is not a reliable recovery process.	At no point in the manuscript was it suggested that casting would not work. Again, an emotive response to what was a fair representation of casting as agreed by the other reviewer to this manuscript. The reliability of casting is not a factor that has ever been scientifically explored and it is a fair point to highlight this lack of underpinning research which is all the manuscript did.
6	The vast majority of identifications of impressions in 3D substrates are because a cast was made.	This is a closed view and disputed by both the literature (Bodziak 2017) and the practitioners I spoke to.
7	It would appear to me that the SfM method would precede casting, and therefore is not competing against casting. In the author's own response, they said "our aim is not to compare, but to illustrate the potential", thus I see no need in the abstract or paper to say anything at all negative about casting or that diminishes or discourages casting.	Again this illustrates the strength of opinion that casting is prime despite the literature.

8	I don’t understand why this amount of ‘inaccurate’ rhetoric about casting is necessary to your paper.	The objective assessment of casting is repeatedly referred to as inaccurate rhetoric. Yet there is no published paper to date that addresses issues of accuracy and precision with it.
9	Those who are knowledgeable and experienced in making casts of a variety of three-dimensional impressions would not agree with your assessment.	The author has made in the region of 50 -100 casts in the research timeframe (3 yrs), having been trained as part of an undergraduate degree by a former CSI. This is arguably many more than a CSI would complete in the same time frame, at least in the UK.
10	If you want to say something like ‘casting might not always be convenient and/or the essential casting materials may not be available’ that is fine.	This sentence skirts around some of the aspects of casting that should be brought to the literature
11	Please note that although there have been one or two papers that advocated the use of fixatives, as a matter of practice and experience, and the consensus of examiners, fixatives are not recommended or used or necessary. Thus, I would simply eliminate this portion. Again, it is also really not ‘on topic’ for your paper.	A further reference to the experience and consensus of examiners being enough to conclude a scientific foundation. There are several references attesting to work using fixatives (e.g., Battiest et al. 2016; Sabolich 2018).
12	As someone who has been involved in research, some of the most important aspects of research of this type is to have an experienced and qualified forensic consultant as part of your research team so, in the end, you can actually make a valid comparison between existing recovery methods, such as properly taken forensic photographs and casts, with the actual results of your SfM method provides.	The aim of this paper was not a competition between methods. This reviewer appears unable to accept that an introduction of a new technique should be anything other than a direct (and aggressive) competition against current methods. The aim of this paper was to highlight the potential of SfM, showing examples of how it may produce superior visualisation in some circumstances.
13	The author needs a realization of the impracticality of a new technique on a police force that has to acquire this equipment and must be trained	The reviewer is determined to misunderstand the issues. In response an estimate of the time taken to capture a 3D model via SfM was made and to take the pictures for a footprint takes about 70 seconds. No equipment is needed other than a crime scene camera.
14	It appears that a great deal of photographs must be taken from many angles. One of your cited papers suggests around 20 images for each impression. I would ask the author if they have any understanding that this amount of time and photography seem far more problematic and unrealistic to expect from a crime scene tech	A clear misunderstanding of the time in which an SfM model can be undertaken. This has been clarified to the reviewer. The time taken to prepare a cast, wait for it to set and package it up appropriately is not mentioned here. It is interesting that time is a concern, yet a concern that does not apply to casting.

	than what is required to photographically document an impression using traditional methods.	
15	I cannot recommend this paper in its current form. When new techniques and equipment are proposed to complete methods that have been in place for decades, there should be a more symptomatic and un-biased approach to testing and promoting these techniques.	The reference to a technique that has been in place for decades in other disciplines illustrates a problem. Given the criticism that the forensic footwear discipline has taken for relying on opinion-based evidence, one would think this attitude no longer has a place. Just because a technique has been used for a long period of time attests nothing to its reliability if such reliability has never been scientifically tested.
16	I am highly supportive for research for new methods, but the author's research, in my opinion, does not provide any of what is needed to introduce a new technique and equipment to the forensic community for consideration or to prove it is an improvement over existing methods.	An unfortunate view which, if accepted by the editorial team will halt research. Has this occurred for other attempts at introducing digital recovery methods?

Table 37. Reviewer comments from the Journal of Forensic Identification in response to the submission of Paper 3.6 - Recovering of 3D footwear impressions from sandy substrates: technical note on the contribution of SfM photogrammetry

Table 19 in Paper 3.3 is a comprehensive guide to the benefits and limitations of techniques. Comparisons can be drawn, but the aim of the table is multifaceted. All methods will invariably have limitations, the perfect method rarely exists. To isolate the limitations of other methods and use these to steer research is a logical approach. In this instance the complimentary use of methods is a useful way of approaching the table data. Using one technique to strengthen another can be achieved, in much the same way an impression would be both photographed and cast. Pairing an existing method with SfM photogrammetry would be beneficial and plausible as:

One: The addition of photogrammetry does not require any more equipment than a CSI already has.
Two: The data obtained is not likely to be identical, SfM can in some circumstances provide superior visualisation as seen in paper 4.2 and will only equal or increase quality of evidence.
Three: SfM photogrammetry is non-invasive.
Four: The crime scene element of the method takes a matter of seconds, not rendering it impractical.

Combinations of data, if practicable, should therefore be further explored by CSI's to increase data quality as opposed to replacing one method with another. This may or may not take a natural course further down the line if it appears any method is becoming redundant. For example, combining 2D and 3D (Photography and Photogrammetry/Laser Scan), or digital and non-digital (Cast and photogrammetry/laser scan) provides complimentary data. It may be assumed that this additional effort is not required, specifically with volume crime. It is there, however, that the addition could have the most impact when considering the increased options for intelligence gathering. Adding 3D data to footwear databases such as the NFD is a very real possibility and considerable gains may become apparent in due course when incorporating 3D data into pattern-matching algorithms.

Paper 4.2 is the closest to a technique comparison found in this research. It looks to understand how features are visualised in casting, 2D photography and photogrammetry and the results can either be taken as singular academic research effort for each method or as a collective to see if one method succeeds where another doesn't. Broadly they show that superior visualisation is seen when recovering with SfM, although there is scope for this to be an insignificant finding due to the limitations of the study and the vast array of variables that exist within impression evidence recovery. The finding is, however, particularly significant when considering accompanying comparative logistics of each method (Table 19). Although straightforward, these can be very difficult to portray to resistant practitioners, as seen in Table 37.

Theme 3 – Presentation of data, suitability and potential of digital analysis reporting in footwear evidence

One of the clear advantages of SfM methods is the ability to bring statistical methods to bear in the subsequent analysis of 3D models. This speaks to the ongoing debate and in some cases tension between the role of the expert examiner's opinion and a bald and supposedly objective statistical statement.

The goal of any form of forensic reporting is to use a method which does not over or understate the strength of the forensic evidence. The disciplines in which this is most relevant are those which have previously and currently, rely on expert opinion. As is often the case, there is a compromise required, it is not an either/or situation. Paper 3.5 demonstrates the use of statistical analysis in barefoot impressions in carpet which can be used to strengthen an expert's opinion with digital comparison data rather than replace the expert altogether. Within vertebrate ichnology the provision of digital comparisons has removed the tendency for a single trace to be used to make a hypothesis as the logistical advantages of recovery come back into play. This can be equally applied to the idea of one impression being cast and used to provide forensic evidence as opposed to a whole set of impressions. Since the introduction of SfM methods in the ichnology community many users have gone from showcasing visually pleasing colour rendered models and believing that to be the extent of the methods' benefits, to providing valid digital comparisons. (personal communication, Professor M Bennett, November 2020).

Such uses of digital data in the forensic context therefore satisfy the requirements of a scientifically valid comparative technique that the discipline has been challenged to provide. Beyond simple comparative procedures such as this, is an appreciable library of literature driving the analyses of digital point clouds from qualitative descriptions, to quantitative. The goal of an article by Belvedere et al. (2018) was to provide a method of quantification of similarities of dinosaur tracks, investigating if thresholds can be drawn for comparison. Techniques such as this require little, if any, alterations in order to apply to footwear impressions, as the basis of the comparisons and aims of assessing morphological variability equally apply to this forensic context. The outputs of many digital point cloud analyses may be much easier to explain to a lay audience than a statistical Bayesian model due to less ambiguity of terms, and no introduction of estimated data.

Attempts have been made to move footwear evidence into a discipline that reports its findings in a statistical manner, reporting rates of probability or likelihood ratios, broadly known as a Bayesian approach. Evett et al. (1998) attempted such a formalisation of interpretation, offering a potential framework. This approach encouraged examiners to assign numerical values to each aspect of the examination and include values such as the quantity of shoes sold and population of people in the area into a probability equation. A final numerical value would be provided to either provide strong or weak support for the proposition that the suspect was the offender. Over time, inconsistent approaches across countries and examiners can be seen (Bodziak 2012), with the UK an example of a country where some adaptions to a Bayesian model have been made and the US an example of a country who has largely remained consistent with a traditional footwear mark evaluation (Bodziak 2012). Whilst it is clear from reports such as the NRC (2009) that a move towards statistical reporting is inherently necessary, there remains to be seen an approach that satisfies both the world of footwear examiners and reporting bodies alike. The question is; therefore, can the introduction of digital recovery increase the quality of reporting for three-dimension impressions evidence, and satisfy both camps. Again, it is about providing a compliment to the role of an expert rather than replacing them.

Research question eight of this thesis focuses on the idea that a technique that shifts a sub-section of a discipline into the use of digital data, could be an opportunity for a superior reporting style. There is a vast arena of tools, already in use in other communities, that can be brought across and applied here, many of which are evidence throughout this project in a forensic context. For example, the digital comparison of point clouds using cloud to cloud comparisons (Seen in papers 3.2, 3.3, 3.4, 3.5, 3.7, 4.1) and the compare function within bespoke photogrammetry software, DigTrace (Seen in paper 3.3 and Appendix II: Figure 7). This function allows two or more traces to be superimposed over one another and the points between each cloud to be compared statistically, showing areas of statistical variance visually as in Figure 21, and therefore a great tool for explaining a comparison to a court. Figure 21 is an example of this as it is a comparison of impressions made by two identical shoes with different levels of wear. Standard deviation between the models has been calculated and a threshold was set so that only areas which show statistical variance at 95% are shown (Bennett and Budka 2018). This illustration of reporting styles may not suit all examiners and many may suggest they are not superior to current comparison techniques. The strength of digital data and subsequent reporting, like many other aspects of this research, may well be in their complimentary use and the strengthening of existing methods, not the replacement.

Chapter six: Conclusion

To conclude this thesis, we can look at the foreword from the 2020 annual report by the forensic science regulator Dr Gillian Tully (Tully 2020). Many points raised in this message deeply resonate with the work completed in this project. Some key examples of areas of change required and areas of resistance are highlighted, just as have been experienced and illustrated within. The notions of transparent reporting, clear limits of knowledge and a mention of the scope that these concepts apply to are all in line with what is achieved within this project and what will hopefully provide a foundation for future work in this area. Tully's (2020, p2) mention of innovation speaks to the core purpose of this research and places this research exactly where it is intended, as provisions of solutions and innovations that contribute to the way forward.

> *"Whether it is data science, computer science, physics, chemistry, biology or another discipline, forensic science should be firmly rooted in good science. Courts should not have to judge whether this expert or that expert is 'better', but rather there should be a clear explanation of the scientific basis and data from which conclusions are drawn, and any relevant limitations. All forensic science must be conducted by competent forensic scientists, according to scientifically valid methods and be transparently reported, making very clear the limits of knowledge and/or methodology. Implementation of quality standards is a means to this end, ensuring a systematic approach to scientific validity, competence and quality. It therefore remains my absolute priority to publish a standard for the development of evaluation opinions, to ensure that this systematic approach to quality covers all scientific activities from crime scene to court.*
>
> *Some practitioners and leaders understand quality. They may be (and indeed should be) challenging about the detail of how to adopt the standards and may rightly point out the need for additional resources. However, they seek to use the requirement to adhere to quality standards to innovate in terms of process and/or technology and, in doing so, they bring about positive change. Often, they are truly inspiring. Others misunderstand. They may grudgingly implement standards, but in a way that cripples their productivity and locks staff into rigid protocols, no matter what the case requires. Or they may devote much time and energy to avoiding compliance, arguing against change and sticking to "how we've always done it". The problem is that technology has moved on. "How we used to take anti-contamination precautions" is no longer fit for purpose in a world*

> *where the sensitivity of DNA methods has increased by several orders of magnitude. "How we used to do digital forensics" is no longer fit for purpose in a world where data volume and complexity have ballooned, and a substantial subset of the data required is in the cloud. Throwing massive volumes of extracted data to investigators, who generally lack the tools and methods to interrogate the data effectively, just shifts a problem; a more integrated approach could be transformative.*
>
> *Leadership and innovation are critical, because trying to transpose quality standards onto ineffective processes without change only succeeds in adding inefficiency to ineffectiveness."*

6.1 Research questions answered

A degree of scientific foundation for the use of SfM photogrammetry as a 3D footwear impression recovery tool has been accomplished within this work. This has been determined through investigation into the method's accuracy and precision as well as determining levels of repeatability and reproducibility. Cumulative results successfully address ***Research Question 1***.

A key advantage of SfM is the ability to determine error rates for individual environments, inclusive of the user, procedure and software errors that may occur. This level of transparency is rarely achievable nor utilised in relation to traditional recovery methods. The use of SfM in likely environments has been assessed and error rates can be seen to match those of industry standards. Higher errors can be seen in snow and wet substrates for which recommendations have been made to lessen the error rate disparity. These findings successfully address ***Research Question 2***.

The visualisation of impression features has been assessed for both current and proposed methods in a number of differing instances and in relation to a number of features. Superior visualisation with the use of SfM photogrammetry is a difficult term to guarantee but results show great promise. The results show that SfM can offer favourable results and highlight the potential in multiple environments, but any direct comparison should be evaluated in a contextualised trial undertaken by operationally competent examiners. As such, the answer to ***Research Question 3*** is a subjective one.

The practical advantages of SfM are significant to this research in many ways. Aside from scientific validity, the practicality of the method is paramount to the use of the method in an operational setting. This research has aimed to provide objective scrutiny of the practicalities of all methods currently used to recover 3D impression evidence in order to provide context. In comparison with 3D casting, the practicalities of SfM can be split into, recovery advantages, analysis advantages and reporting advantages. These include, but are not limited to, a ~70 second on scene recovery time, no requirement for an electrical output and a completely non-destructive protocol. Analysis options are increased as outputs can be digitally compared and 3D printed. Reporting styles can be both simple and fit into a statistical model as is encouraged. Further practicalities include a digital output that is easy to be shared and stored. These simple and easily discoverable advantages can explain the trajectory of SfMs popularity in other communities. Specifically to footwear recovery, discoveries in this work show SfM can provide increased visualisation of both class and individual characteristics. This project has also highlighted that many of these practicalities mean impressions that are currently only recovered in 2D can be recovered in 3D, such as carpet. These results satisfy ***Research Question 4*** and provide an exciting base for which the forensic community can build.

The current determination of a scientific foundation for casting is weak and although experts are confident in the accuracy and precision the method produces, there are no studies available to evidence this. The experiments using casting throughout this project have highlighted the practicalities of this method, or their lack of, as well as an assessment of the reliability. Repeatably accurate results can be seen as a result of these experiments but a cloud of uncertainty has arisen over the repeatability to recover individual features accurately. These results answer, to a degree, ***Research Question 5***.

A dataset aimed at looking at the rate of acquisition of identifying footwear characteristics was unfortunately halted by the 2020 pandemic. The information gained, before the halt had to be called, provided the author with valuable experience. Predominantly, the experience of watching the behaviour of features over time. I.e., how features can appear and disappear in patterns or at random, in higher rates on lower quality shoes and lower rates dependant on the substrates they contact and the frequency in which they are worn. Understanding these elements brings the authors knowledge of footwear closer to those seen in operational practitioners. ***Research Question 6*** therefore continues to be a great area to study with many quantitative opportunities for analysis available.

Highlighting any additions, or reductions, in footwear evidence value through the use of a digital recovery method was the secondary main aim of this project. Once a scientific foundation had been laid, the aim shifted to the value and impact the method may have on a relatively under researched area of forensic science. Although it may be argued that anything can be successfully cast, the reality of the situation is that the unpractical protocol of recovering impressions this way limits the frequency in which it occurs. It is a fair assumption that many 3D footwear impressions are overlooked due to a reluctance to cast them. Equally, time pressures mean ten 3D impressions may be present at a scene and only one, potentially deemed the most ‘valuable’ cast, leaving the unexplored potential of the other impressions to 2D photography or not being recovered at all. The value of footwear impression evidence needs to be considered on two planes to understand why the current recovery method is limiting value. These are the evidential-value and the intelligence-value. Recovering 10 impressions using a digital non-destructive method would take 10 x ~70 seconds and could provide a vast amount of intelligence that would otherwise be overlooked. The value can therefore be seen in (1) the practicalities of the method increasing frequency of type of evidence, (2) the nature of the method increasing the surface types able to be recovered in 3D and (3) the subsequent intelligence value of that evidence. The cumulative results of many of the papers in this project attest to the value of SfM and answer ***Research Question 7***. Appendices I,II and III further illustrate the value of SfM recovery in evidential and intelligence contexts, via the use of crime scene examples.

The nature of the reporting for all of the research papers included in this project is, intentionally, a combination of simplicity and ensuring scientific validity. The acceptance of the analysis style into peer-reviewed journals is an important milestone of the project. Highlighting to the forensic community, a different reporting style, that could be further explored for court use. ***Research Question 8*** has been partially answered with this work, with huge scope for continued research.

The significant findings from this project include the rather basic, but crucial, assurance that the accuracy of the method is both discoverable and on a level that falls in line with current methods. Any research into the digital recovery of 3D footwear impressions at this stage would be both an original and significant contribution as it is such an unexplored area that has huge research potential. In order to make an impactful contribution, aims and objectives were set out to cover as many aspects as possible, whilst including enough depth to make them meaningful. There are no revolutionary results that will have immediate effect on the forensic science community, instead, a portion of the race run, and a baton handed to the community to elevate this research into revolutionary change that can be possible.

6.2 **Limitations and areas of further research**

The limitations of this project come from the tension between objective assessment and the need to advocate for a new technique. Trials and adoption by practitioners are part of the challenge. There is a level of uncertainty around what should be provided at this stage and an element if one excuses the aphorism of ‘chicken and egg’. Without user engagement one cannot test the technique, but without having tested the technique one struggles for engagement.

With a large portion of this project completed by one individual, the levels of consistency achieved between experiments is high but this is also in turn a limitation. Valid comparisons between techniques are not an option without the introduction of trained professionals to undertake data collection. Any comparisons therein are therefore provided with caveats that whilst examples of other techniques are included and comparisons have been made, their validity is limited because an expert on one of these other techniques may be able to push the limits of that technique. One is reminded by the reviewer comment in Table 37 ‘anything can be cast’. However, much of the work that includes methodologies, datasets and instructions can, at a later date, be repeated and enhanced with the use of operational experts in each area. The division between the academic approach and the operational norms is also a limitation of this work. It is likely scientific validity will need to be assessed further by the International Organisation for Standardisation (ISO), as is currently the standard recovery technique adhered to. It is hoped that this project will be the catalyst for this to be undertaken.

Areas of further research can be broadly categorised into the general workflow of SfM evidence.

Recovery

- SfM recovery of impressions in snow, increasing consistency and quality of output
- Comparative experiments of 3D recovery using different methods
- Inclusion of further evidence types beyond footwear, including, tire marks, tool marks, 3D fingerprint impressions, writing analysis.

Analysis

- Investigations into both the value and enhancement of the comparative analysis available with digital data

Reporting

- Studies highlighting new and clear ways of reporting digital data comparisons.

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Appendix I: Crime scene example 1

Scenario: A female has reported the theft of her car in the early hours of the morning. The suspect has taken the vehicle from the driveway of the female's residence but has not been seen by the female or any of her neighbours. CCTV shows the car speeding down a road adjacent to the victim's house. Local police have discovered the vehicle in a car park nearby with items missing. The female had left a laptop and camera in the boot of the car and these are now missing along with a pair of designer sunglasses that were in the glovebox. The car has been dusted for fingerprints, but the suspect looks to have worn gloves as no prints were found that did not belong to the owner. There was a layer of snow/slush on the ground at the time the car was abandoned and footsteps can be seen around the vehicle. Footwear impressions have also been collected from outside of the house where the vehicle was taken from. Additional tracks can be seen around the vehicle belonging to the first police officer on scene and have been ruled out of analysis. CCTV of the car park shows a female leaving the car park but does not show from which car. She can be seen to be carrying a large holdall and is wearing what appear to be Nike Shoes as indicated by a visible Nike Logo on the side of the shoe.

This potential suspect has been identified and been brought in by local police officers. She was not carrying the stolen items at the time of her arrest. Her shoes were seized at custody so that test impressions could be made.

Evidence presented	
Item Number	Description
1	Photograph of suspect shoe side (Figure 1A)
2	Photograph of suspect shoe side (Figure 1B)
3	Photograph of suspect shoe sole (Figure 1C)
4	Photograph of scene, tracks highlighted (Figure 2A)
5	Photograph of scene, tracks highlighted (Figure 2B)
6	Photograph of scene, tracks highlighted (Figure 2C)
7	Crime Scene Sketch (Figure 2D)
8	DigTrace Colour Render of track A (Figure 3A)
9	DigTrace Colour Render of track B (Figure 3B)
10	DigTrace Colour Render of track C (Figure 3C)
11	Surfaced Model of track A (Figure 3D)
12	2D Static Test impression (Figure 4A)
13	2D Dynamic Test impression (Figure 4B)
14	DigTrace Colour Render of dynamic impression of test shoe in Bubber^{TM} (Figure 4C)
15	DigTrace Standard Deviation Comparison of track B found near the vehicle in the car park and track D from the track found at the home where the vehicle was taken. (Figure 5A)
16	DigTrace 2 point Standard Deviation Comparison of track B found near the vehicle in the car park and track D from the track found at the home where the vehicle was taken. (Figure 5B)

Table 1. Evidence items 1 – 18 for crime scene example 1

Figure 1. Evidence Items 1-3. **A** Vertical photograph of right side of suspect shoe. **B** Vertical photograph of left side of suspect shoe. **C** Vertical photograph of suspect shoe sole.

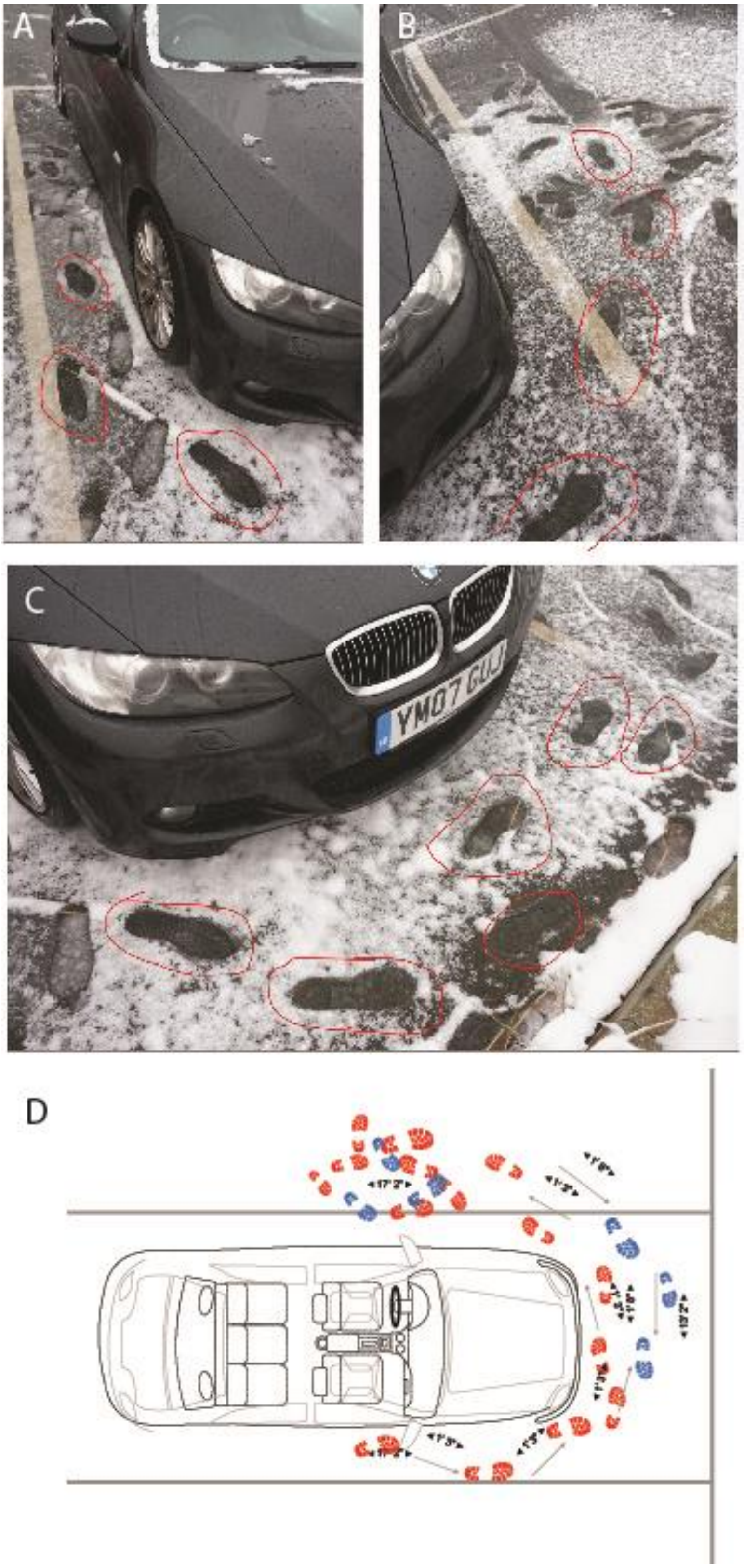

Figure 2. Evidence Items 4-7 **A**, **B** and **C** Photographs of impressions in situ, impressions highlighting in red. **D** Crime scene sketch of area impressions were located. Red showing one direction of movement and blue showing directional change.

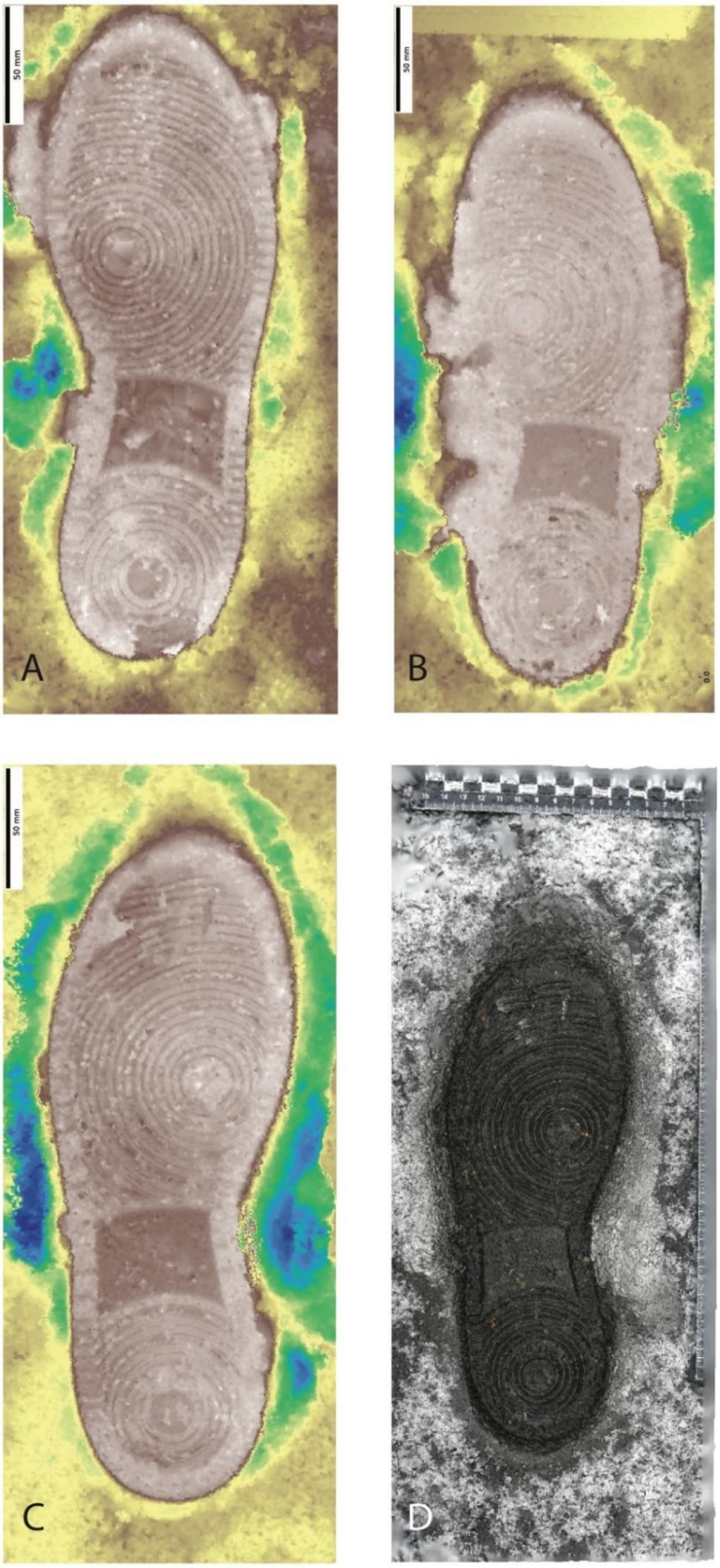

Figure 3. Evidence Items 8 -11. **A, B, C** DigTrace colour renders of tracks a,b and c. Scaled, cropped and aligned to orthogonal view in DigTrace. **D.** Example of a surfaced (Delauney) 3D model using one of the tracks located.

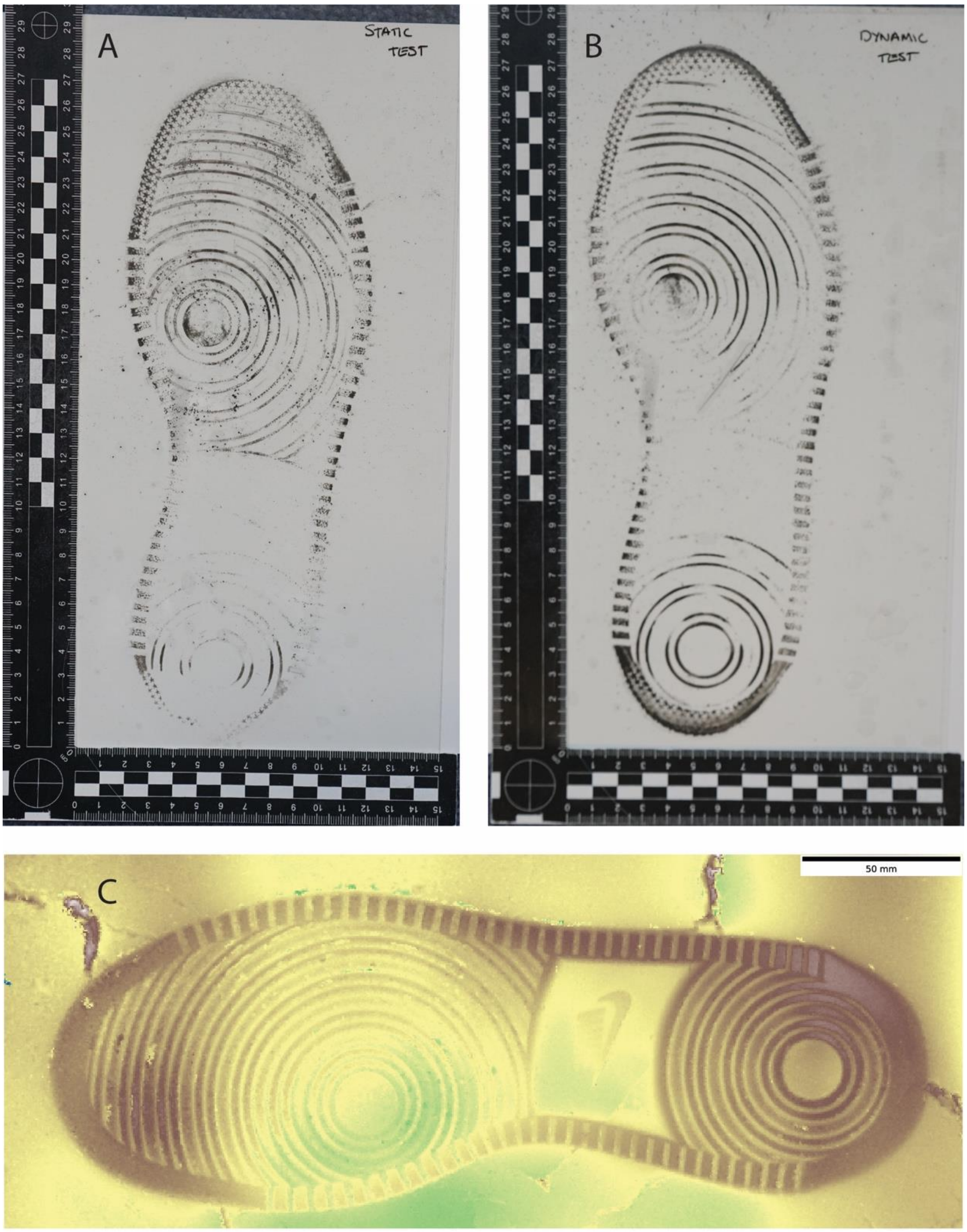

Figure 4. Evidence Items 12-14. **A** 2D static test impression. **B** 2D dynamic test impression. **C** DigTrace Colour render (Scaled, cropped and aligned to orthogonal plane in DigTrace) of dynamic 3D test impression in Bubber^{TM}

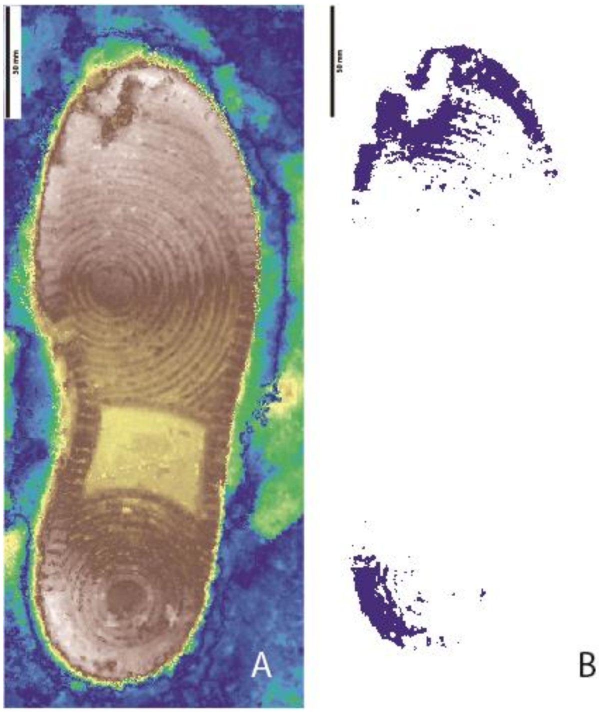

Figure 5. Evidence Items 15-16. **A** The standard deviation between the two co-registered shoe prints track B and track D. **B** A version with a 2 standard deviation threshold applied showing areas (blue) that are statistically significant at 95%.

Analysis:

- Two-dimensional test impressions created to identify class and individual characteristics of suspects seized shoes. Both static and dynamic prints taken. No visible individual characteristics or appearance of general or individual wear.
- Three-dimensional test impression using Bubber^{TM} taken to identify class and individual characteristics. No visible individual characteristics or appearance of general or individual wear.
- Three-dimensional models created of three tracks from car park and one track from driveway. Scaled cropped and interpolated in DigTrace and colour depth renders produced. Measurements taken of impression.
- One fully surfaced model created using Poisson mesh in MeshLab.
- One comparison of two tracks undertaken. One track from the car park and 1 from the driveway. Standard deviation map accompanied by two

standard deviations showing statistically significant areas between tracks.

Evidential Value: The evidential value of the evidence presented is limited but useful. Without any unique wear patterns or unique characteristics, we cannot determine a positive identification between the suspect’s seized shoe and impressions found at the scene. The DigTrace comparison shows a strong match between the tracks found at both scenes suggesting it was indeed the same pair of shoes making both of the tracks. This doesn’t, however, allow us to link the suspect to the shoes. The suspect's seized shoes appear to have a very minimal degree of wear suggesting they are fairly new or at least have not been worn much. As such it could be suggested that there are more than one pairs of shoes in circulation which could have made the same impression as found at the two scenes.

Intelligence Value: Whilst the evidential value of the evidence is not strong, the evidence has intelligence value. These tracks have been input into a database to see if there are any matches with other crimes scene evidence. This could potentially lead to further charges as the suspect can be immediately questioned on other crimes if matches are found.

Conclusion: The tracks found at both scenes appear to have been made by the suspect. It is, however, difficult to conclude a positive identification due to the lack of individuality on the shoe sole.

Appendix II: Crime scene example 2

Scenario: An assault has taken place inside a house on a quiet cul de sac. The homeowner opened the door to whom she believed to be a charity collection volunteer who forcible entered the residence. The suspect is alleged to have attempted to assault the homeowner and fled upon hearing another resident come down the stairs. The police were quickly on the scene and were able to pick up the suspect a few roads away after receiving a brief description from the victim. A forensic team was asked to check the property and its surroundings for evidence and located several footwear impressions. Detectives investigating the incident are particularly keen to identify the size and brand of shoe. There have been several incidents of a similar description in neighbouring forces where footwear marks were also found. If the impressions are from the same size and make of shoe it will allow officers to start a line of questioning regarding the whereabouts of the suspect at the times those offences were committed.

Evidence presented

Item Number	Description
1	DigTrace Colour Render of dynamic test impression in Bubber^{TM} (Figure 6A)
2	Crime Scene Sketch (Figure 6B)
3	Photograph of impression A in situ (Figure 6C)
4	Photograph of impression B in situ (Figure 6D)
5	Photograph of impression C in situ (Figure 6E)
6	DigTrace Colour Render of track A (Figure 7A)
7	DigTrace Colour Render of track B (Figure 7B)
8	DigTrace Colour Render of track C (Figure 7C)
9	DigTrace compare overlay track A-C (Figure 7D)
10	DigTrace compare overlay track A-B (Figure 7E)

Table 2. Evidence items 1- 10.

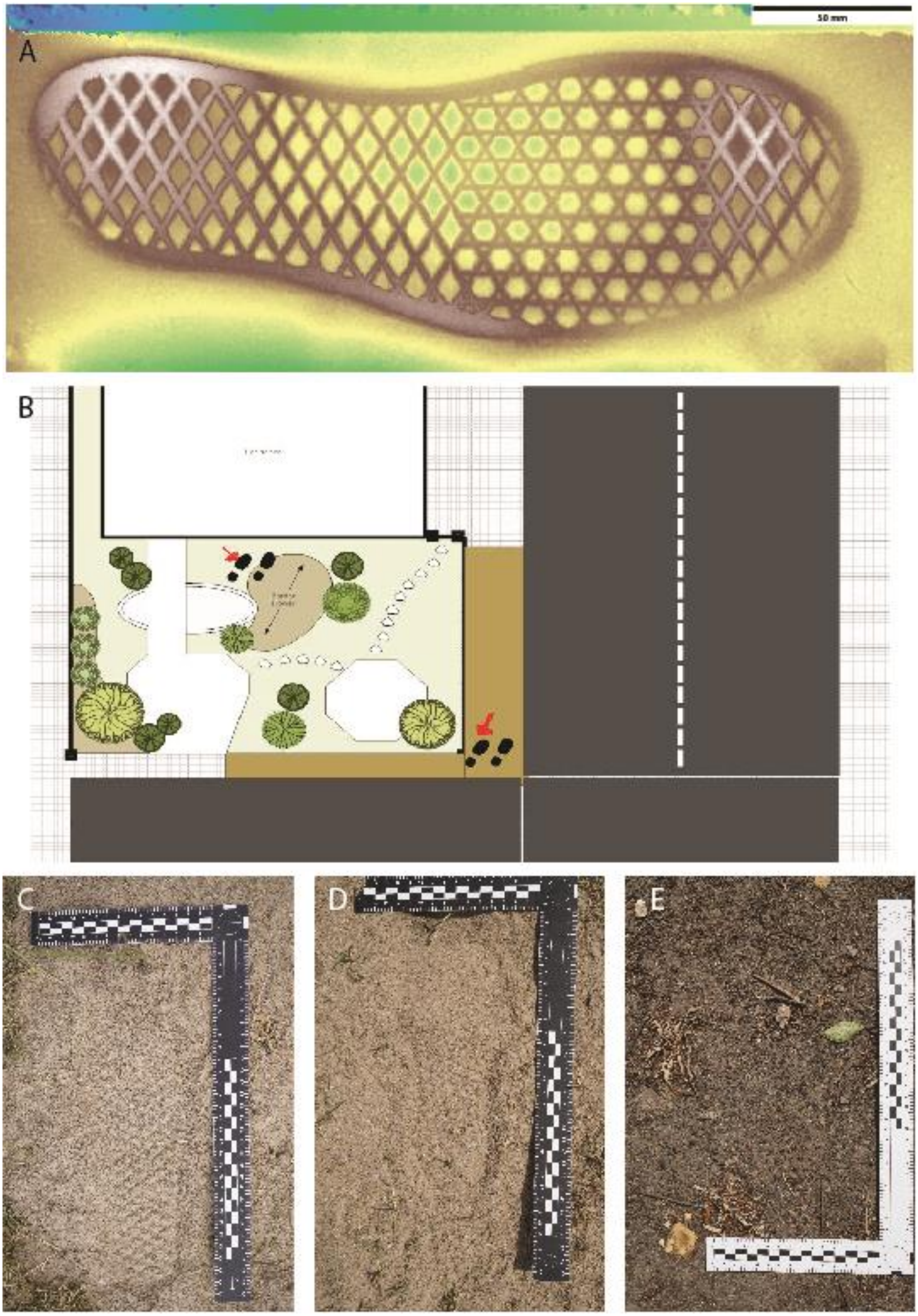

Figure 6. Evidence items 1-5. **A.** DigTrace Colour render (Scaled, cropped and aligned to orthogonal plane in DigTrace) of dynamic 3D test impression in Bubber$^{\text{TM}}$ **B.** Crime scene sketch. **C,D and E.** Photographs of impressions in situ.

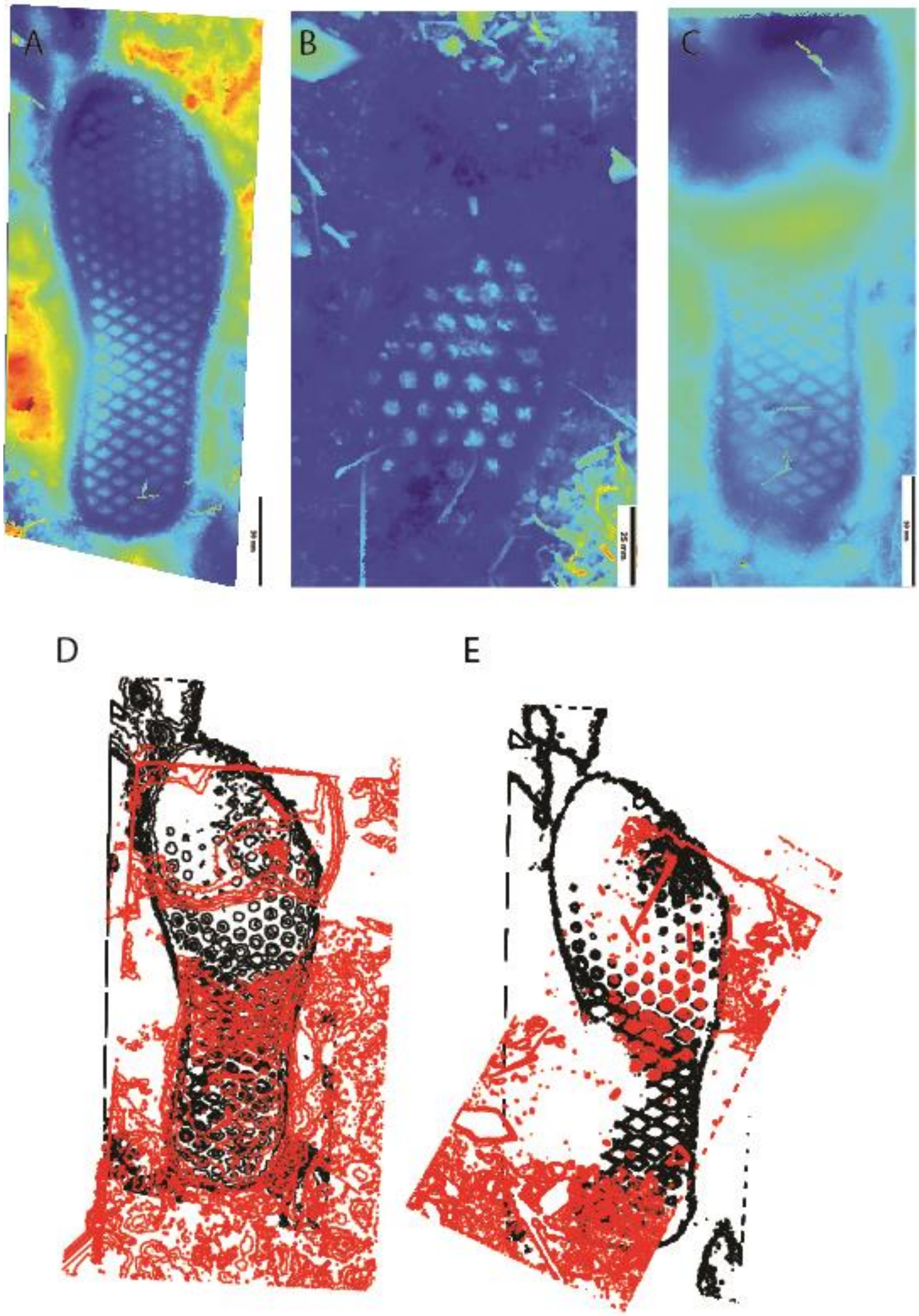

Figure 7. Evidence items 9-13 **A,B,C.** DigTrace Colour renders of three tracks recovered (Scaled, cropped and aligned to orthogonal plane in DigTrace). **D.** DigTrace compare overlay track A-C **E.** DigTrace compare overlay track A-B

Analysis.

- A test impression was taken using the suspect's shoe in Bubber^{TM}. A model was built of this impression using DigTrace. The shoe is a size 6 and brand Vans.
- All three impressions found were photographed and models built using DigTrace. A visual analysis shows they are all made from a shoe of likely the same size and the same brand. Compared images show how each impression links to another.

Evidential Value

- The evidential value of these impressions is limited for the following reasons: The shoes are very popular and the pattern left in the impression is by a sole owned by a large number of people. This means that positively matching the shoe and the impressions is less likely. Secondly, the shoe looks to be fairly new and not worn, there is no evidence of a huge amount of wear or any characteristics that would make a positive identification easier. The medium in which the impressions were left is made up of very fine grains of sand. Any minute detail of wear or RACS may not have been left due to this.

Intelligence Value

- The intelligence value of these impressions is high as both size and brand have been easily identified. This information can now be run through the national footwear database and matched with similar impressions left at other scenes.

Conclusion

- The impressions left behind at this scene are indicative of those left by the suspect in custody. They have been made by a size 6 Vans shoe. This is the same size and brand of those worn by the suspect. The intelligence value of this information led to the charging of the suspect of three separate criminal offences.

Appendix III: Crime scene example 3

Scenario: A convenience store has been broken into and vandalised during the night. Items have been left strewn around the floors of the aisles and the cash register broken into. Two suspects have been detained but there is little evidence linking them directly to the crime. They were seen running from the store and picked up by police nearby. Both suspects were wearing balaclavas and gloves. Shoeprints have been found in food items discarded around the shop.

Evidence presented	
Item Number	Description
1	3D Model of shoeprint in slice of bread (Figure 9)
2	Custody print of suspect A shoes seized (Figure 8 A, B)
3	Custody print of suspect B shoes seized (Figure 8 C, D)

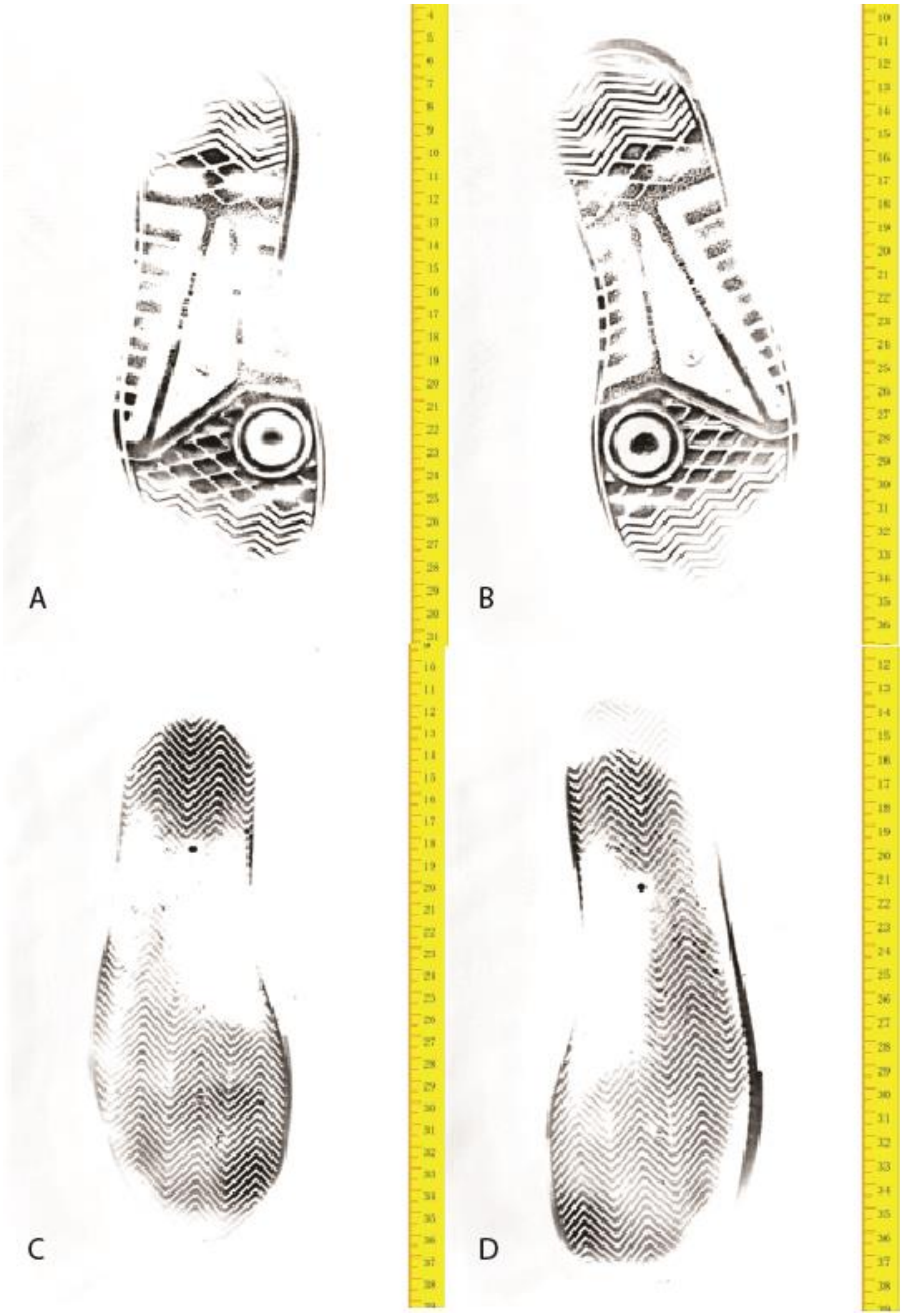

Figure 8. Evidence items 2-3 **A,B,C,D**. Custody prints obtained with an Everspry shoeprint scanner.

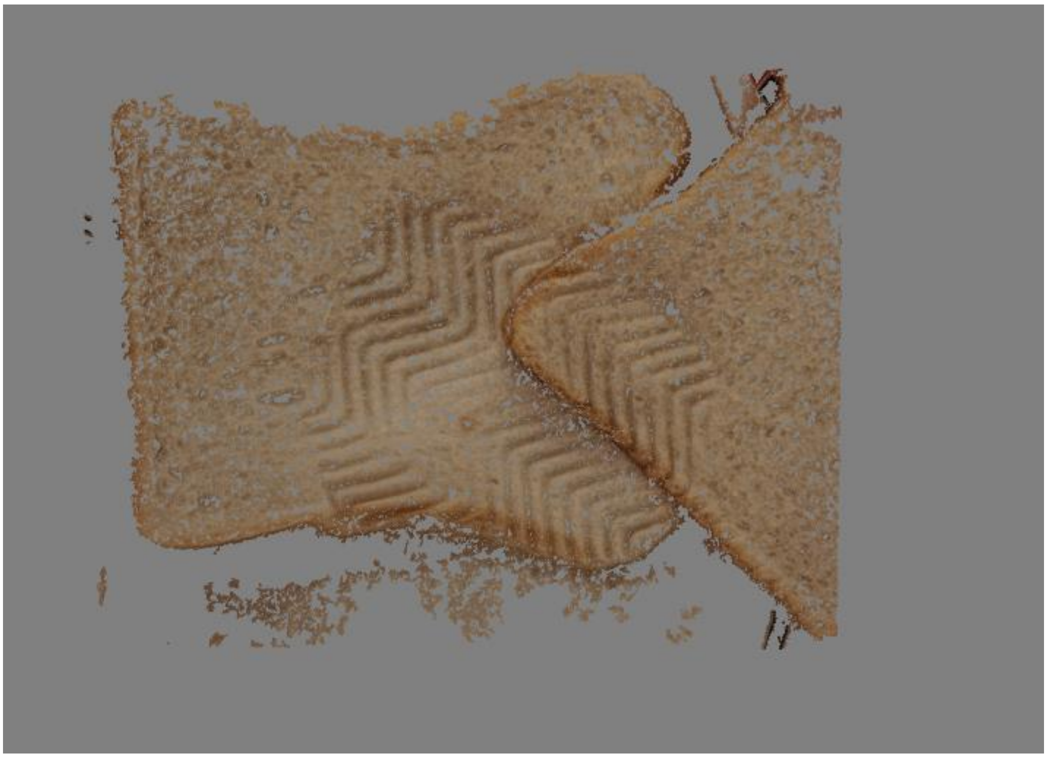

Figure 9. Evidence item 1 – 3D point cloud viewed in DigTrace of an impression in bread, recovered via SfM photogrammetry.

Analysis: Both suspects have walked on a footwear scanner once they have reached the custody suite and the images are sent for comparison to the 3D model. The model has been created by the collection of 29 images taken by forensic officers at the scene. They have then been uploaded into DigTrace and the model has been scaled and cropped.

Evidential Value: Low – No unique features can be determined from the impression to successfully identify the suspect's shoe as the shoe that made this impression. The pattern is very common.

Intelligence Value: High – Make and model easily determined from DigTrace model.

Conclusion: In the opinion of the examiner the questioned footwear impression in bread could have been made by suspect B. It can be seen that the pattern in the bread closely correlates with that of the suspect B's scanner prints. This is presented to the suspect in interview and he admits to the convenience store burglary.