Article

Recovery of Footwear Impression Evidence Using Portable Three-Dimensional Scanning Technologies: A Pilot Study

Julia Harvey [1]
Eugene Liscio [2]
Amanda Lowe [3]
Theresa Stotesbury [1]

Abstract: Current methods used to document and collect footwear impression evidence are destructive and lack high-resolution three-dimensional detail. This study explored the use of non-invasive three-dimensional scanning technologies to document and collect the three-dimensional characteristics of footwear impression evidence. Footwear impressions created in sand and garden soil using a sneaker and a boot (n=4) were documented and collected using a digital single-lens reflex (DSLR) camera using the photogrammetric method, a Polyga Compact L6 structured light scanner, and an Artec Space Spider structured light scanner. The Polyga Compact L6 acted as the high-resolution baseline that most closely represented the actual footwear impressions. Point clouds and meshes were compared in CloudCompare to determine the level of intra-variability between the Artec Space Spider and photogrammetry technologies. The Artec Space Spider was the most accurate of the methods for documentation and collection for all impressions with a mean absolute distance of 0.148 mm or less. Photogrammetry had a mean absolute distance of 0.176 mm or less. It was found that three-dimensional scanning technologies are viable as a compliment for two-dimensional photographs and casting when collecting footwear impression evidence.

[1] Faculty of Science, Forensic Science, Ontario Tech University, Oshawa, Canada

[2] ai2-3D Forensics, Vaughan, Canada

[3] Forensic Identification Services, Ontario Provincial Police, Orillia, ON, Canada

Introduction

Footwear impression evidence is currently documented by taking two-dimensional colour photographs with oblique lighting or collected for three-dimensional detail using casting materials [1 - 3]. However, when dealing with impressions with a significant amount of varying depth, it is difficult to accurately represent the scale and impression in a single plane and the result is still a two-dimensional representation of a three-dimensional object [4, 5]. Casting can collect three-dimensional characteristics and preserve the depth of an impression, however, it is a destructive process that gives the collector only one chance to recover the footwear impression evidence [6 - 9].

Over the past decade, advances in three-dimensional scanning technologies have been on the rise [10, 11]. Three-dimensional scanners capture information in the form of a cloud of geometric points, each defined by an X, Y, and Z Cartesian coordinate, that are meshed together to represent the scanned three-dimensional surface [4, 12]. There are several methods which can be used for three-dimensional collection, but the most common for footwear impression evidence are photogrammetry and structured light scanning.

Photogrammetry uses overlapping two-dimensional photographs taken at various oblique angles to create a digital three-dimensional model [2, 13, 14]. Photogrammetry software will match pixels within the overlapping portions of the photographs and compute the camera positions and camera orientations, as well as place the pixels in three-dimensional space [2, 14].

Structured light scanners use triangulation methods consisting of a projector, camera, and an internal processing unit [15]. A known laser dot or fringe pattern is projected onto the object being scanned and any three-dimensional components of the object create distortions to the projected pattern [7, 15]. The distortion caused by the three-dimensional object is captured by the camera and a three-dimensional point cloud is calculated by the internal processing unit [7, 15].

The documentation of footwear impressions at a crime scene requires a three-dimensional scanning system that is portable and easy to use [15]. Footwear impression evidence may be found on uneven surfaces or varying substrates. A handheld device to capture footwear impression evidence provides the

examiner with a non-destructive and contact-free method to obtain a three-dimensional measurement, ultimately decreasing the possibility for contamination and destruction of detail while increasing the amount of available data for analysis. The digital data collected typically has a resolution in the tenths of micrometers (μm) [15]. Results produced through three-dimensional scanning can help increase the amount or quality of the feature set in the impression that can be observed during the comparison process. Although the user will input and define measurements, comparisons conducted by software packages between impressions will be automatic [6]. Results could also be used as a demonstrative tool in court as a digital three-dimensional model or as a physical model using three-dimensional printing.

The goal of this research was to evaluate two three-dimensional scanning systems and photogrammetry methods as a proof of concept for their ability to analyze three-dimensional footwear impression evidence made in garden soil and sand.

Methods

Two footwear impressions were created in two types of substrates using two types of footwear. Sakrete tan coloured natural beach sand and Specialties Robert Legault Bella Terra natural garden soil were used as the substrates. The first type of footwear was a Canada/USA size 7.5 Women's Nike SB Bruin Low Sneaker and the second was a Canada/USA size 7.5 Women's Blundstone 585 Classic boot. The author created each footwear impression by wearing the chosen footwear and stepping into each substrate using full body weight (58 kg).

The created footwear impressions were then documented using two-dimensional photography and three-dimensional methods including Photogrammetry, the Polyga Compact L6 Monochrome scanner, and the Artec Space Spider structured light scanner. Each method was performed on the same impression once for each substrate and footwear type.

Polyga Compact L6

The Polyga Compact L6 was used as the high-resolution baseline for this study upon which all the other three-dimensional technologies were compared. The Polyga Compact L6 was chosen as the high-resolution baseline due to its large field of view and purported high three-dimensional point accuracy (a similar Polyga scanner has been tested in the medical field [16]).

The Polyga Compact L6 is a tripod mounted three-dimensional structured light scanner with up to 0.08 mm three-dimensional point accuracy when used within the 60 cm – 70 cm optimal working distance. The Polyga Compact L6 can capture a field of view from 265 mm x 225 mm to 375 mm x 345 mm.

The Polyga Compact L6 was situated on a slight angle towards the impression within the optimal working distance. Figure 1 shows the Polyga Compact L6 set-up for capturing scans. In total, two scans from opposing sides were collected using the Polyga Compact L6 for each impression.
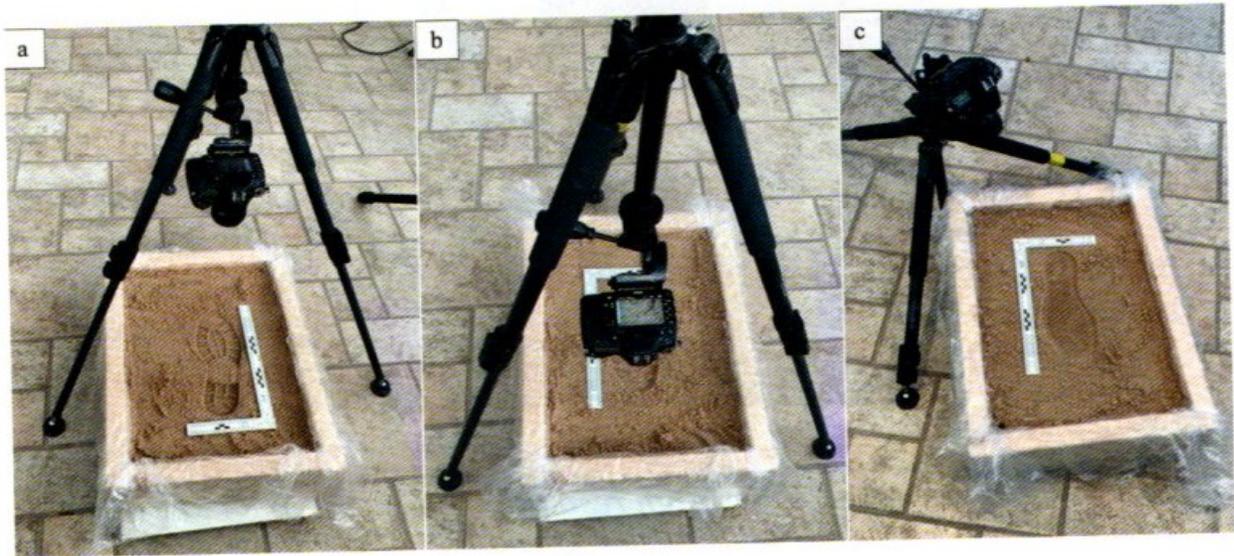

Figure 1

Polyga Compact L6 scanner (high resolution baseline) to collect a 3D footwear impression.

Using FlexScan 3D, which is the Polyga program used to process scans during and after collection, all the impressions were generated as a mesh using the High Dynamic Range (HDR) mode. Exposure settings were 5.00 ms to 15.00 ms for the sand impressions and 120.00 ms to 160.00 ms for the garden soil impressions. The difference in exposure time was due to the differences in brightness between the sand and the garden soil. After collection, the scans were manually aligned, registered using the fine alignment tool, finalized using precise merge,

and then exported as an .OBJ file, which is the standard three-dimensional image format for various three-dimensional software programs.

Photogrammetry

A Nikon D7100 camera with a 60 mm macro lens mounted on a tripod was used to capture the photographs for photogrammetry. Mid-range photos, close-up photos, and angled photos were taken for each of the impressions tested with a total of 27 photos taken for each impression. Starting from the toe-end of the impression and moving towards the heel-end, overlapping mid-range photographs from approximately 30 cm directly above the impression were taken. Close-up photographs were taken using the same method as the mid-range photographs but from a distance of approximately 10 cm above the impression. Angled photographs of the deep edges of the impression were also taken. The lighting source while taking the photographs remained in the same location for all photographs. The camera set-up for each set of photographs is pictured in Figure 2.

Figure 2

Camera setup used for taking mid-range (a), close-up (b), and angled (c) photographs for photogrammetry use.

Photographs of each impression were uploaded to a photogrammetry processing program, 3DF Zephyr (3DFLOW, Verona, Italy), . Point clouds for each impression were created using sparse reconstruction and dense reconstruction. Using default settings, a mesh extraction was completed resulting in a three-

dimensional model consisting of polygons. The mesh was exported as an .OBJ (Wavefront 3D Object) file.

Artec Space Spider

The Artec Space Spider is a handheld three-dimensional structured light scanner with up to 0.05 mm three-dimensional point accuracy and up to 0.1 mm three-dimensional resolution. The higher accuracy and resolution provided by the Artec Space Spider is accompanied by a smaller working distance of 20 cm to 30 cm. As the Artec Space Spider was moved over the surface of the impression within the optimal working distance, data was collected in frames. The collection process using the Artec Space Spider is pictured in Figure 3.

Figure 3
Artec Space Spider scanner collecting a 3D footwear impression.

Using Artec Studio 16, which is the Artec program used to process scans during and after collection, frames collected during scanning were aligned and merged with global registration. Some of the impressions collected in sand contained noise so a three-dimensional resolution of 0.15 mm and outlier removal was conducted, as was recommended by the Artec Studio 16 manual [17]. Sharp fusion with a three-dimensional resolution

of 0.15 mm was used to finely fuse the scanning frames. The resulting mesh was exported as an .OBJ file.

CloudCompare Three-Dimensional Comparison

The generated photogrammetry and Artec Space Spider meshes were uploaded to CloudCompare V. 2.12.0 for comparison against the Polyga high-resolution baseline. The meshes were transformed into point clouds by sampling approximately 1,000,000 points on the mesh. The Artec Space Spider and photogrammetry point clouds were manually aligned with the Polyga baseline mesh. Any irrelevant data from outside of the impression was manually removed using the Segment tool. The point clouds were then automatically aligned to the Polyga baseline mesh using the Fine Registration (Iterative Closest Point) tool. The cloud to mesh distance for each of the points was computed using the Cloud-to-Mesh Distance Computation tool. A histogram of resulting distances was generated for each three-dimensional technology.

Results

Side-by-side comparisons of the footwear outsoles, two-dimensional photographs and each three-dimensional model from a perpendicular angle are shown in Figure 4 (boot in sand), Figure 5 (boot in soil), Figure 6 (sneaker in sand), and Figure 7 (sneaker in soil).

| Footwear Outsole | 2D Photograph | Polyga | Artec Space Spider | Photogrammetry |
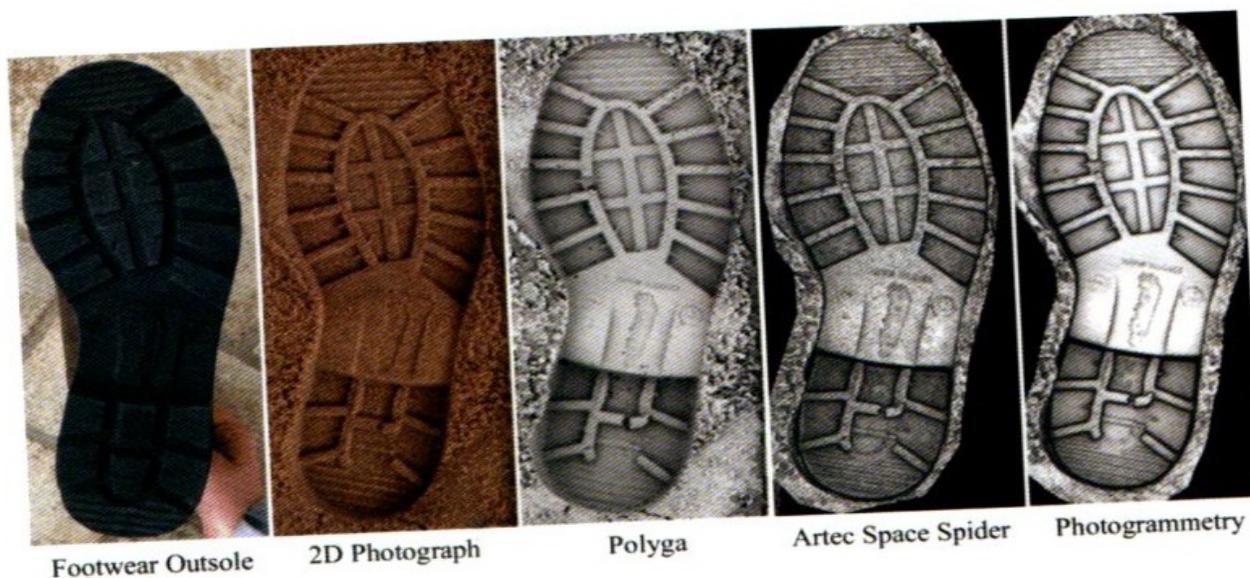
Figure 4

Side-by-side comparisons of the footwear outsole, 2D photograph, Polyga model, Artec Space model, and Photogrammetry model for the boot sand impression.
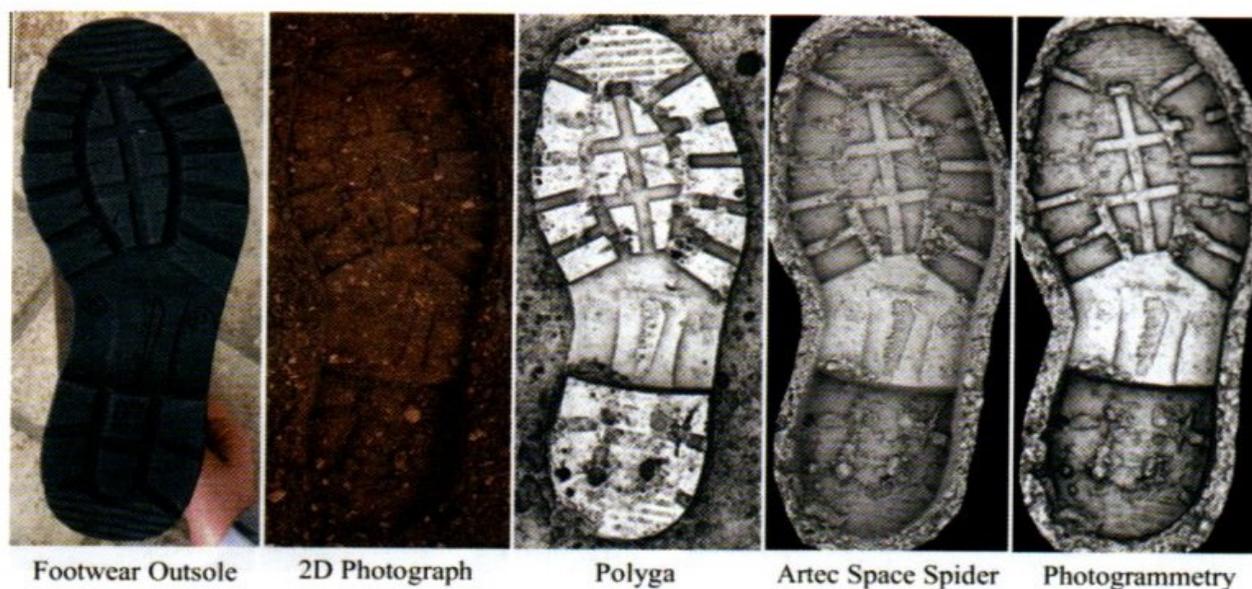
Footwear Outsole **2D Photograph** **Polyga** **Artec Space Spider** **Photogrammetry**
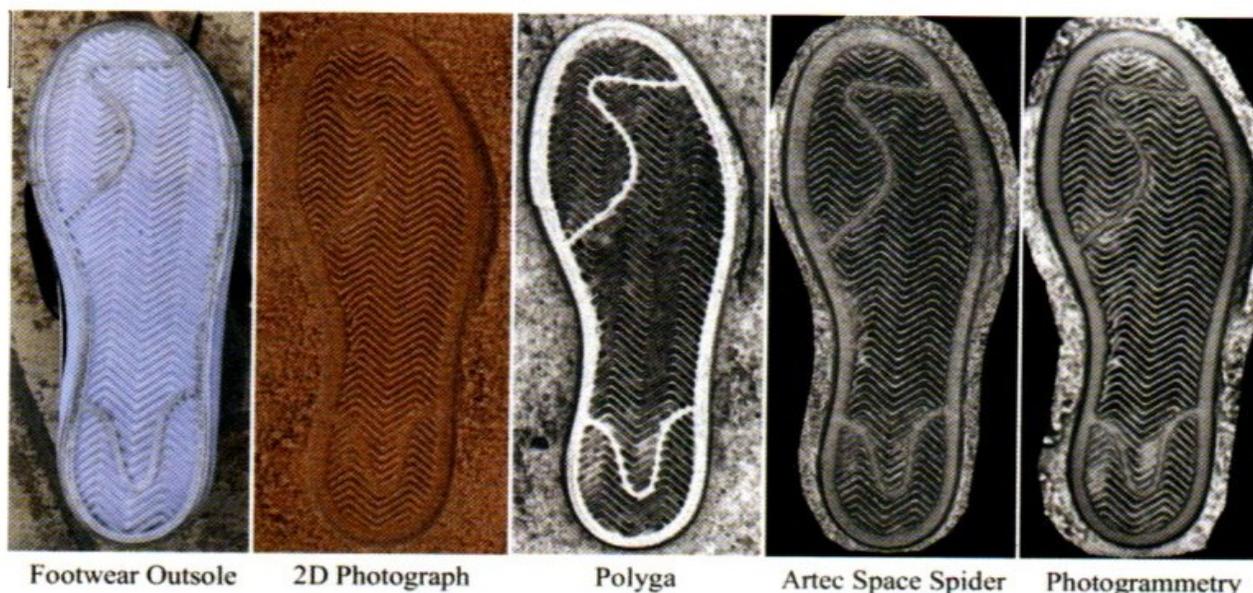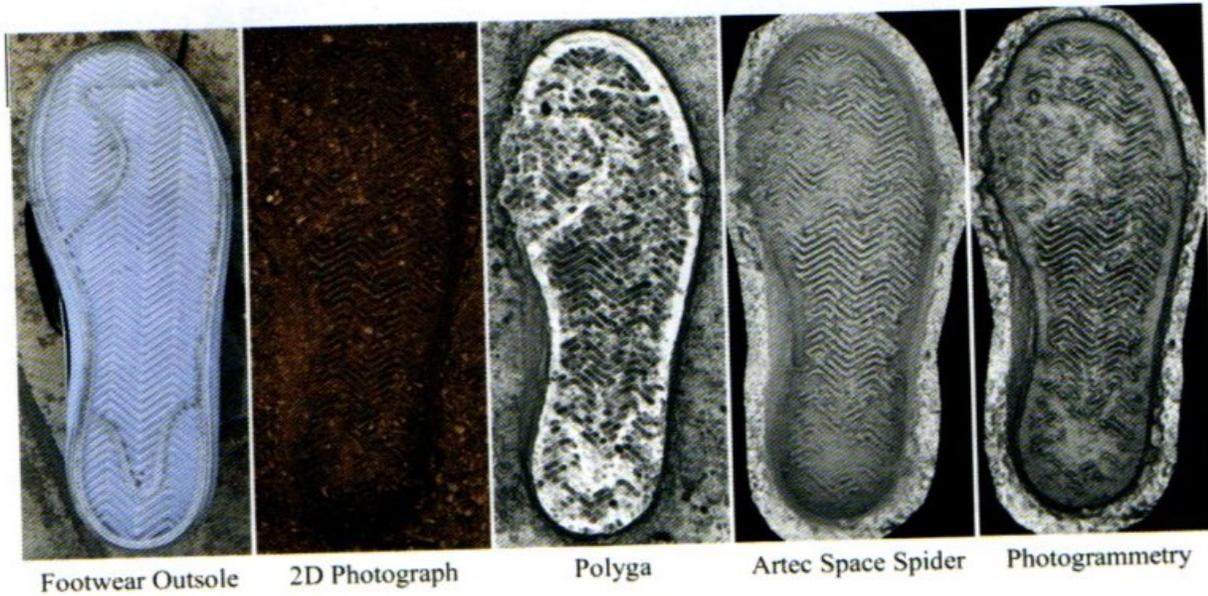
Figure 5

Side-by-side comparisons of the footwear outsole, 2D photograph, Polyga model, Artec Space model, and Photogrammetry model for the boot soil impression.

Footwear Outsole **2D Photograph** **Polyga** **Artec Space Spider** **Photogrammetry**

Figure 6

Side-by-side comparisons of the footwear outsole, 2D photograph, Polyga model, Artec Space model, and Photogrammetry model for the sneaker sand impression.

| Footwear Outsole | 2D Photograph | Polyga | Artec Space Spider | Photogrammetry |

Figure 7

Side-by-side comparisons of the footwear outsole, 2D photograph, Polyga model, Artec Space model, and Photogrammetry model for the sneaker soil impression.

CloudCompare Three-Dimensional Alignment

Root mean square (RMS) data collected from CloudCompare for the alignment of Artec Space Spider impressions compared to the baseline ranged from 0.161 mm to 0.227 mm between all impressions, with an average RMS of 0.202 mm ±0.026, 95% CI. Alternatively, RMS data collected from CloudCompare for the alignment of photogrammetry impressions ranged from 0.194 mm to 0.242 mm between all impressions, with an average RMS of 0.215 mm ±0.018, 95% CI. The RMS values for the Artec Space Spider and photogrammetry impression registrations are reported in Table 1.

Technology	Impression	Number of Points Used	RMS (mm)
Artec Space Spider	Sand Boot	50,000	0.161
	Sand Sneaker	50,000	0.227
	Soil Boot	50,000	0.198
	Soil Sneaker	50,000	0.221
Photogrammetry	Sand Boot	50,000	0.205
	Sand Sneaker	50,000	0.220
	Soil Boot	50,000	0.194
	Soil Sneaker	50,000	0.242

Table 1

Root mean square values for Artec Space Spider and photogrammetry point cloud registration with Polyga mesh.

Distance Computations

The distances between the Polyga baseline mesh and the point clouds created from the Artec Space Spider and photogrammetry were calculated for all the impressions as an absolute value. The exact number of points used for each impression comparison are shown in Table 2.

Technology	Impression	Number of Points Used	Mean Distance (mm)	Std. Deviation (mm)
Artec Space Spider	Sand Boot	999,535	0.109	0.119
	Sand Sneaker	999,545	0.140	0.184
	Soil Boot	999,146	0.140	0.141
	Soil Sneaker	1,000,187	0.148	0.151
Photogrammetry	Sand Boot	999,913	0.134	0.155
	Sand Sneaker	1,000,157	0.151	0.158
	Soil Boot	999,773	0.144	0.131
	Soil Sneaker	1,000,394	0.176	0.169

Table 2

Absolute distances for all impression comparisons between Polyga mesh and 3D collection technology point clouds.

The results of the distance computations for each impression were displayed as a mean distance and the standard deviation. The mean absolute distances of the Artec Space Spider impressions compared to the baseline ranged from 0.109 mm to 0.148 mm between all impressions, with an average absolute distance away from the baseline of 0.134 mm ±0.017, 95% CI. The mean absolute distances of the photogrammetry impressions compared to the baseline ranged from 0.134 mm to 0.176 mm between all impressions, with an average absolute distance away from the baseline of 0.018 mm ±0.017, 95% CI. The overlapping impressions computed in CloudCompare along with the absolute distance height ramps for the Artec Space Spider and photogrammetry are shown in Figure 8.
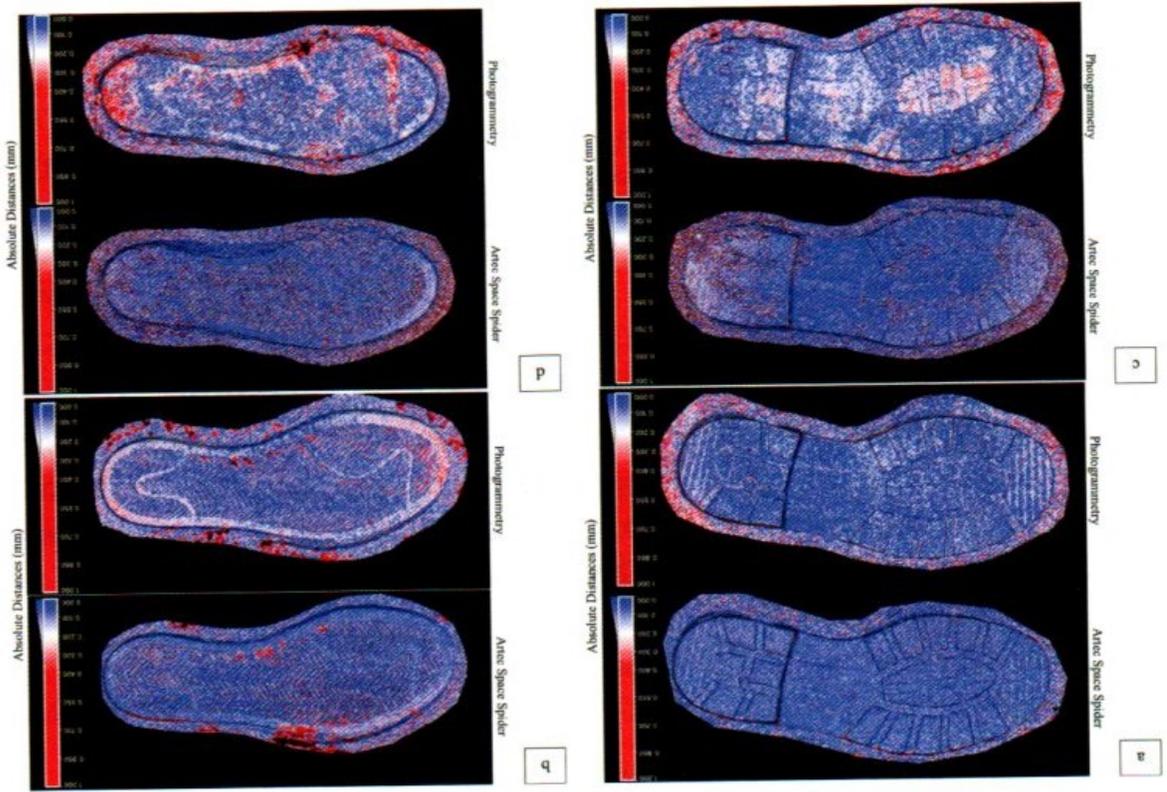

Figure 8

Artec Space Spider and Photogrammetry point clouds for (a) sand boot, (b) sand sneaker, (c) soil boot, and (d) soil sneaker impressions including absolute distance height ramps.

The absolute distances for all the impressions collected using the Artec Space Spider and photogrammetry are displayed as coloured scalar histograms in Figure 9. For the sand boot impression, 97% of points collected using the Artec Space Spider had an absolute distance of 0.359 mm or less, while 97% of the points collected using photogrammetry had an absolute distance of 0.402 mm or less. For the sand sneaker impression, the Artec

Space Spider showed that 97% of points had an absolute distance of 0.449 mm or less and 97% of the photogrammetry points had an absolute distance of 0.457 mm or less. The soil boot impression showed that 97% of Artec Space Spider points had an absolute distance of 0.465 mm or less, while 97% of the photogrammetry points had an absolute distance of 0.426 mm or less. For the soil sneaker impression, the Artec Space Spider showed that 97% of points had an absolute distance of 0.457 mm or less, and 97% of the photogrammetry points had an absolute distance of 0.484 mm or less.
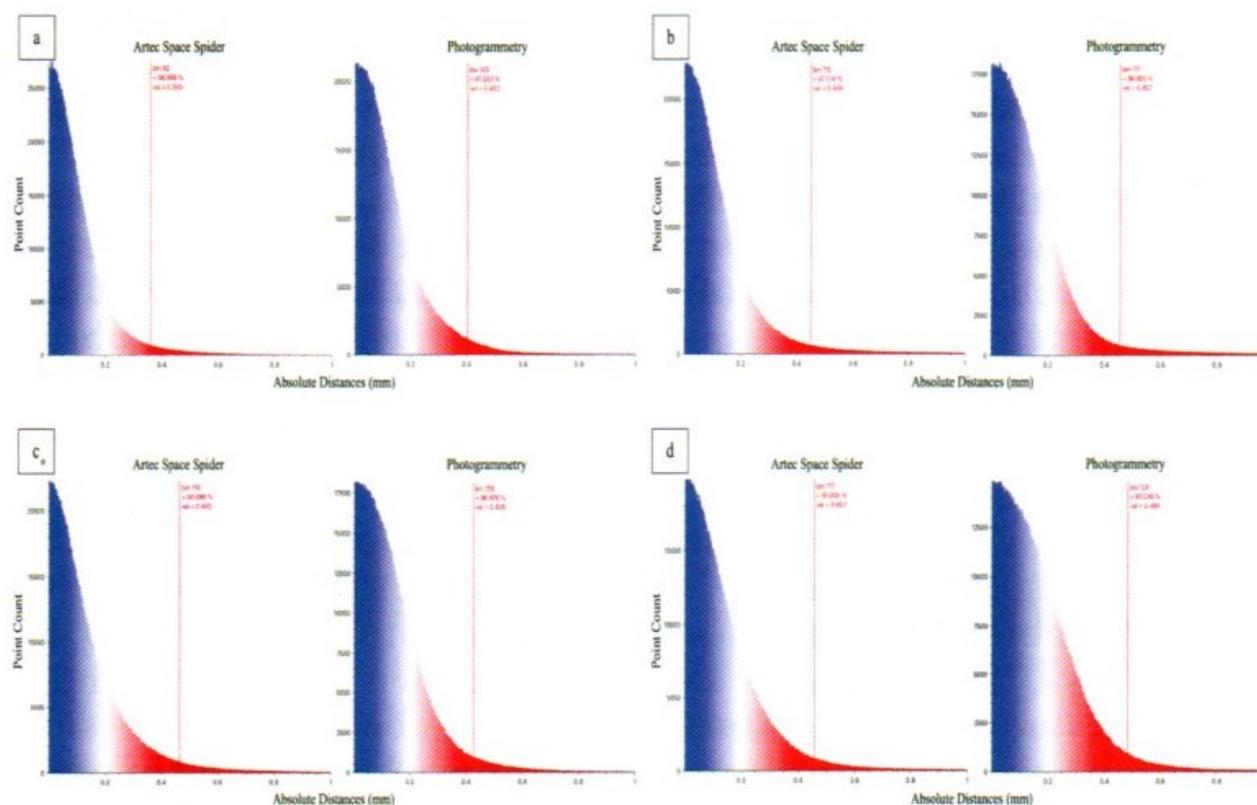

Figure 9

Cloud-to-mesh absolute distance computations for Artec Space Spider and Photogrammetry for (a) sand boot, (b) sand sneaker, (c) soil boot, and (d) soil sneaker impressions. The red line indicates absolute distance that 97% of points lie within.

Discussion

This study investigated several three-dimensional documentation and collection technologies for footwear impression evidence. The Polyga Compact L6 three-dimensional scanner was used as the high-resolution baseline scanner to most closely represent the created footwear impressions. The Polyga Compact L6 would be a viable option for use by forensic professionals for the collection, documentation, and analysis of footwear impression evidence. However, it is important to note that the

Polyga Compact has relatively large overall scanner dimensions. A large scanner may not be portable to, or practical at, all crime scenes. Furthermore, the Polyga Compact L6 requires a laptop, software, and 120V AC to operate. At a price point of approximately $14,000 CAD, the Polyga Compact L6 is not the most expensive 3D collection technology tested in this research, however it could still be a considerable investment for any law enforcement agency to consider.

Although the Artec Space Spider has a small field of view, the portable nature of this scanner allows for the capture of fine details within footwear impressions at many locations with high accuracy and precision. The live view provided while scanning may be useful to ensure that evidence is fully captured when at a crime scene. However, the Artec Space Spider also requires a laptop, software, and 120V AC to operate. The Artec Space Spider is the most expensive 3D collection technology used in this research with a price of approximately $30,000 CAD. The higher price of the Artec Space Spider is justified in its ability to collect high accuracy and high-resolution results while also being portable.

Overall, the Artec Space Spider had the lowest Root Mean Square (RMS) and absolute distance values across all the impressions. For all the impressions collected using the Artec Space Spider, 97% of points had an absolute distance of 0.492 mm or less. These results are consistent with results found in previous studies [4, 14]. Absolute distances between impressions collected using the Artec Space Spider have been tested in previous studies and found an average absolute distance of 0.806 mm or less [4]. The results found in previous studies confirm that the results found in this study are comparable to the current threshold of **three-dimensional** collection technologies, if not better.

One of the main purposes for including photogrammetry in this study was that law enforcement agencies and crime scene investigators already have extensive experience with taking high quality examination photographs of footwear impression evidence. Therefore, this three-dimensional collection technology may cost less and be easier to integrate into existing procedures for many law enforcement agencies, but it will add time to current collection procedures, as photogrammetry procedures documented in the literature suggest that 20 photographs be taken for each impression [12, 14].

The average RMS and absolute distance values for photogrammetry were higher than the Artec Space Spider, but it is

important to remember that photogrammetry is highly dependent on the quality of the photographs used. It is possible that photographs taken closer to the impressions may have resulted in lower RMS and absolute distance values. These results, however, are still consistent with results found in previous studies [4, 14]. Previous studies explored the intra-variability between impressions collected using photogrammetry and found that 90% of points had an absolute distance of less than or equal to 0.771 mm [14]. The more stringent threshold of 97% used in this study demonstrates that the results found are within a reasonable range and that the collection technologies used are more accurate.

The manual removal of irrelevant data from outside of the impressions during CloudCompare comparisons may have altered results. Due to the manual use of the Segment tool to remove data, not all the impressions had identical outlines. The differences in outlines may have created broader histograms by including points with large absolute distances from surrounding areas of the impression. Therefore, mean absolute distances may appear larger than they should, or a certain three-dimensional technology may not seem as accurate as another. These issues could be minimized by segmenting directly along the edge of impressions or by testing repeatability between impressions. It is important to note that post-processing and outlier removal used after collection may result in issues regarding the integrity of evidence. When collecting several scans, aligning scans may introduce more error.

Several factors may cause errors when collecting footwear impression evidence using three-dimensional technologies; one of which may be artefacts. Artefacts may be caused by brightness, reflective surfaces, or movement during scanning [18]. If too many artefacts are detected in the original scan, the impression must be rescanned, which may add time to collection methods. One of the problems encountered in this study were the artefacts created in the Artec Space Spider scans, possibly due to the brightness of sand. Although these outliers were easily removed using Artec Studio processes, brightness may still create undetected distortion when collecting footwear impression evidence from lighter surfaces. It is also possible that for some substrates, such as wet soils/mud, three-dimensional scanning may not be appropriate for capturing small class and individual characteristics as the surface may be too reflective [4, 7]. In this case, the surface will have to be prepared to reduce reflectivity in advance of three-dimensional scanning. Preparation can be achieved by spraying the impression with a

three-dimensional scanning primer before scanning. The introduction of blue light instead of white light in structured light scanners, such as the Artec Space Spider, has also allowed for the reduction of reflectivity while maintaining resolution [7].

Although more work is needed to explore the use of three-dimensional scanning technologies in forensic cases, this study helps outline the benefits as well as some areas of concern when using three-dimensional scanning for crime scenes. All three-dimensional scanning technologies used in this study would be of benefit for use in real forensic cases. Currently, many law enforcement agencies have examiners who are already trained in taking high quality examination photographs. Therefore, photogrammetry may be an easy addition to existing procedures as it would only require that examiners take additional photographs without any added equipment. The Artec Space Spider is fast, accurate, and easy to use. Results provided will be quantitative instead of the qualitative, but it may take longer to train examiners on the use of the Artec Space Spider and a laptop, software, and 120V AC are required for operation.

There are numerous benefits of using portable three-dimensional scanning technologies to document and collect footwear impression evidence. Three-dimensional scanning systems are easy to use, mobile, and require minimal preparation time. The collection of footwear impression evidence using three-dimensional scanning technologies is also a non-destructive technique that can be repeated if necessary. Data collected from three-dimensional scanning is available to the examiner immediately and can be evaluated on scene. The digital nature of three-dimensional models created from footwear impression evidence allows for the integration of evidence and data into one package that can be shared between all investigating authorities [12]. The three-dimensional models generated from the questioned impressions, as well as the footwear itself, can also be used as a demonstrative tool in court [19]. Once data is collected using three-dimensional scanning, a physical model of a footwear impression could be made with three-dimensional printing. Although portable three-dimensional scanning technologies have many advantages, it is important to remember their limitations.

Future work may explore the collection of footwear impression evidence using three-dimensional technology for impressions that are incomplete, created in different substrates, or in different weather conditions. This research should include

an assessment of the fidelity of the images to the feature set within the impression, to document any distortion issues related to the technology. Comparing known footwear to unknown impressions would also be beneficial to explore for future use by law enforcement agencies. It is important to determine the effects of the flexion of the foot and natural walking patterns on footwear and impression comparisons for identification or exclusion purposes. It is suggested that footwear impression evidence collected using three-dimensional technologies and casting are directly compared to determine if three-dimensional technologies are viable as a replacement for casting.

Conclusion

The purpose of this research was to examine the resolution of three-dimensional scanning technologies for the documentation and collection of footwear impression evidence. Several portable three-dimensional scanning technologies were compared, not only to determine their suitability, but to outline the benefits that each technology provides.

Overall, this research has demonstrated that three-dimensional scanning technologies are suitable as a compliment to high quality examination photographs. Future research is suggested to determine whether three-dimensional scanning technologies may be a viable replacement for casting to collect footwear impression evidence at crime scenes.

The most accurate technology, the Artec Space Spider, had 97% of points within less than half of a millimetre, which is comparable to, if not better than, current comparison techniques and previous literature. three-dimensional scanning technologies collect footwear impression evidence with similar results as two-dimensional photography, but also provide the ability to view details up close and from all angles. The ability to collect footwear impression evidence as a digital three-dimensional model allows for the integration of evidence and data into one package that can be shared between all investigating authorities [12]. Electronic storage also allows for further examination at any time using a computer with a compatible program [6]. The three-dimensional models generated from the questioned impressions, as well as suspect footwear, may be admissible as a demonstrative tool in court [19]. Although portable three-dimensional scanning technologies have many advantages, it is important to remember their limitations. Reflective surfaces