Investigation into the repeatability and precision of casting 3D impressions

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.

Introduction

In a forensic context casting is the process of pouring plaster, dental stone or some other type of casting material into a 3D impression to recover details of that impression for comparison with test impressions or a suspect's footwear. In the case of dental stone, the casting materials have the consistency of thick cream upon pouring and hardens over time before the impression is lifted and cleaned. This type of method has been used to recover both footwear and tool mark impressions and has a long tradition of use in jurisprudence (Bodziak 2017). Battiest et al. (2016) identified the lack of underpinning research, yet testimony based on the examination of casts has survived multiple challenges, despite the Daubert (1993) guidance which stress the need for techniques to be underpinned by research. Battiest et al. (2016, p782) puts it succinctly casting "has not been well researched beyond basic trial and error". Early research into the technical criteria of casting impression evidence is limited but is present and remains relevant. Du Pasquier et al (1996) and Vandiver and Wolcott (1978) are examples of such work and discuss multiple technical casting material factors. These include, but are not limited to, dimensional stability, detail reproduction and formation of air bubbles or other imperfections. There are a few papers which discuss casting more recently although they focus more on practical solutions such as the use of various surface fixatives to aid casting of snow or loose materials (e.g., Hammer and Wolfe 2003; Battiest et al. 2016). Experiential learning coupled with broad guidance in various textbooks and manuals is the norm (e.g., Cassidy 1980; NPIA 2007; Bodziak 2017).

In the disciplines of palaeontology and archaeology casting of fossilised footprints and other traces, once widespread (e.g., Leakey and Harris 1987) has been replaced almost entirely with digital recovery for the purposes of both analysis and long-term preservation (Bennett and Budka 2018). Initially this was via LiDAR and optical laser scanning (e.g., Bennett et al. 2009), but more recently the use of SfM photogrammetry has become routine (e.g., Bennett et al. 2020; Hatala et al. 2020; Helm et al. 2020a,b). A research paper in these fields reporting some form of 3D trace is unlikely to be published now without digital 3D data and the community has agreed basic methodological standards for collection and reporting (Falkingham et al. 2018). Digital methods have led to a growth in analytical methods and statistical testing (e.g., Belvedere et al. 2018). The widespread availability of 3D printing has also transformed strategies for long-term archiving and conservation. The same revolution has yet to take part in the more cautious and conservative forensic realm. Fundamental to this is a simple question 'why change if casting works and gives reliable results?'

The aim of this paper is to present the results of a simple experiment with the aim of testing the precision and reliability of footwear casting. With precision meaning the reproducibility of a cast in this case, or otherwise put, the ability of an examiner to produce the same results if a cast were to be repeated. This is an impossible study to undertake in the field as the very process of casting destroys the impression after one cast has been made, but has been undertaken here in a controlled environment using a reusable mould. The (2009) NRC report called for forensic methods to be underpinned by rigorous testing of errors to replace the assertion of experts. While belated, this contribution also serves this function with respect to casting.

Method

Casting is normally, unless dealing with a lithified or fixed substrate, a one-time process, i.e., the process of recovery destroys or modifies the evidence. Multiple samples of the same trace are therefore not possible, which is one of the reasons why quantifying precision for casting is quite difficult.

In this experiment we overcome this by creating a footwear impression using a silicone casting medium which creates a flexible mould in this case of the outsole of a shoe. The silicone was prepared as per the manufacturer's instructions and placed in a shallow box or tray made of corrugated plastic. A shoe (UK Size 9, Teva sports shoe) was then placed in the silicone and allowed to find its own level before the mould was set aside to dry for 48 hours. The flexible mould was then carefully removed from the shoe and placed back into a custom-built box so that the sidewalls were supported.

This mould was then used to create 20 identical casts following the latest guidelines from the NPIA (2007) footwear recovery manual. Each cast was prepared using 1000g of dental stone, and 600ml of water as per the manufacture's specifications. The two components were mixed for three minutes when the texture had reached a thick cream. At this point the mixture was poured into the silicone mould. Each cast was left for 1.5 hours before it was removed from the mould taking care to avoid any damage to the mould. All casts were left for a further 48 hours to completely dry. Between each casting the mould was inspected carefully for damage, a reference photograph of the mould was used to assist with this. The casts were then scanned using a Next Engine optical laser scanner which has a stated accuracy of ±0.127 mm and provides an accurate reproduction of each cast. Each scan was imported into DigTrace and auto-rectified such that the principal plane was horizontal. These scans were then compared digitally using CloudCompare which computes Hausdorff Distances, a standard way of comparing two digital surfaces (e.g., Serra 1998; Alt and Guibas 2000). The algorithm compares one point on a mesh to another by finding the nearest point when co-registered. The reported score is a mean of the differences between all the sampled points on the mesh. This approach has been used by Thompson and Norris (2018) and more recently in Montgomerie et al. (2020) as well as Larsen and Bennett (2020) and Wiseman et al. (2020a). Strictly speaking the results not only contain the variation between the casts, but also potential variation between each scan. Note the precision for the scanner is reported at ± 0.127 mm.

Considering reservation, a second analytical process was also followed by taking physical measurements from each cast as a footwear examiner might need to. For each cast the maximum length and width were measured with digital callipers (Yosoo 300mm; ±0.03mm stated accuracy) and measurements were made within the body of the impression between ‘known points’ that were easily identifiable and consistent across all casts. Each measurement was taken five times per cast and a mean computed. According to sampling theory (Benedetto and Ferreira 2012) the error around a mean should increase with sample size, that is the precision should improve to the limits of the technique. By fitting a curve to this data, it is possible to estimate the precision associated with one-time recovery (i.e., N=1). This can be done using the following method:

One: Generate K = 100 bootstrap samples (with replacement) for each value of N in the range between 2 and 20.

Two: Calculate the Standard Error (SE) for each bootstrap sample and each value of N

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).

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

Finally, the shoe used in this experiment has a distinct RACs on the outsole and this is used to illustrate differences between the casts.

Results

The mean distances between two casts, based on the comparison of randomly selected scans thereof, is low with a mean of ±0.014 mm (standard error: ±0.059 mm; Table 27 and Figure 47E). Table 28 shows the data obtained from direct measurement of the casts using the digital callipers. Again, the variation is small and in terms of length, well within a size class between shoes (<0.8 mm). In terms of the computed precision (Table 29, Figure 47) the mean possible variance for footwear length is 1.8 mm with a worst-case scenario of 5.9 mm at a confidence level of 95%. The results are less for width and distances between known points. All told however the variation in measurements that could be determined from a series of casts is relatively modest given the limitations of the experiment.

Figure 48 shows closeup images of part of the outsole with a prominent natural RAC consisting of a cut tread. The images also highlight small scale variation between the casts. Some casts have more significant artefacts for example C6, C9, C10 and C13 in Figure 48 where the dental stone has not faithfully recorded the tread patterns. In addition, many of the casts show evidence of small air pockets between the treads and this could be mistaken by an inexperienced operator in a one-time cast for stones or other inter-tread debris. Bubbles are also a feature of some of the tread surfaces. The shape of the prominent RAC also changed subtly between the casts. It is a flexible membrane on the mould and was easily moved by the plaster. Given that the dental stone was mixed to common consistency and poured in the same way each time there is a considerable amount of small-scale variance.

Scan 1	Scan 2	RMS (Root mean squared)	Mean (mm)	Standard Deviation
13	16	2.92	-0.37	1.65
17	16	1.03	-0.07	0.65
15	3	2.03	0.20	1.17
10	13	2.34	0.14	2.18
19	11	2.95	-0.25	1.85
3	12	1.02	0.08	0.81
6	15	3.14	0.09	2.53
12	6	2.73	0.04	2.00
11	2	2.08	0.15	1.11
20	12	2.52	-0.15	1.50

	Avg		**-0.01**	**1.54**

Table 27. Comparison of randomly selected cast-scan pairs using CloudCompare

	Length (mm)	Width (mm)	Known Point (mm)
	287.38	77.53	101.11
	287.58	77.31	101.18
	278.82	75.34	99.17
	278.69	75.53	98.91
	279.02	75.63	99.16
	278.38	75.25	99.07
	279.59	75.00	100.17
	277.99	73.96	100.31
	279.97	74.11	99.50
	279.44	76.96	101.20
	279.63	76.18	99.25
	281.13	75.56	100.51
	287.79	78.39	100.47
	279.25	76.43	99.41
	286.49	77.31	102.08
	278.65	75.44	99.66
	277.49	75.52	99.18
	279.16	74.68	99.58
	277.57	75.25	99.64
	278.47	74.77	100.42
Mean	280.62	75.81	100.00
St. Error	0.79	0.26	0.20

Table 28. Measurements made from casts showing mean and standard errors.

	Mean Length Error	95% Maximum Length Error	Mean Width Error	95% Maximum Width Error	Mean Known Point Error	95% Maximum Known Point Error
Next Engine Scanner	0.77	2.13	0.42	1.16	0.35	0.89
Casting	1.81	5.96	0.74	1.94	0.51	1.40

Table 29. Error Scores for One Time Use

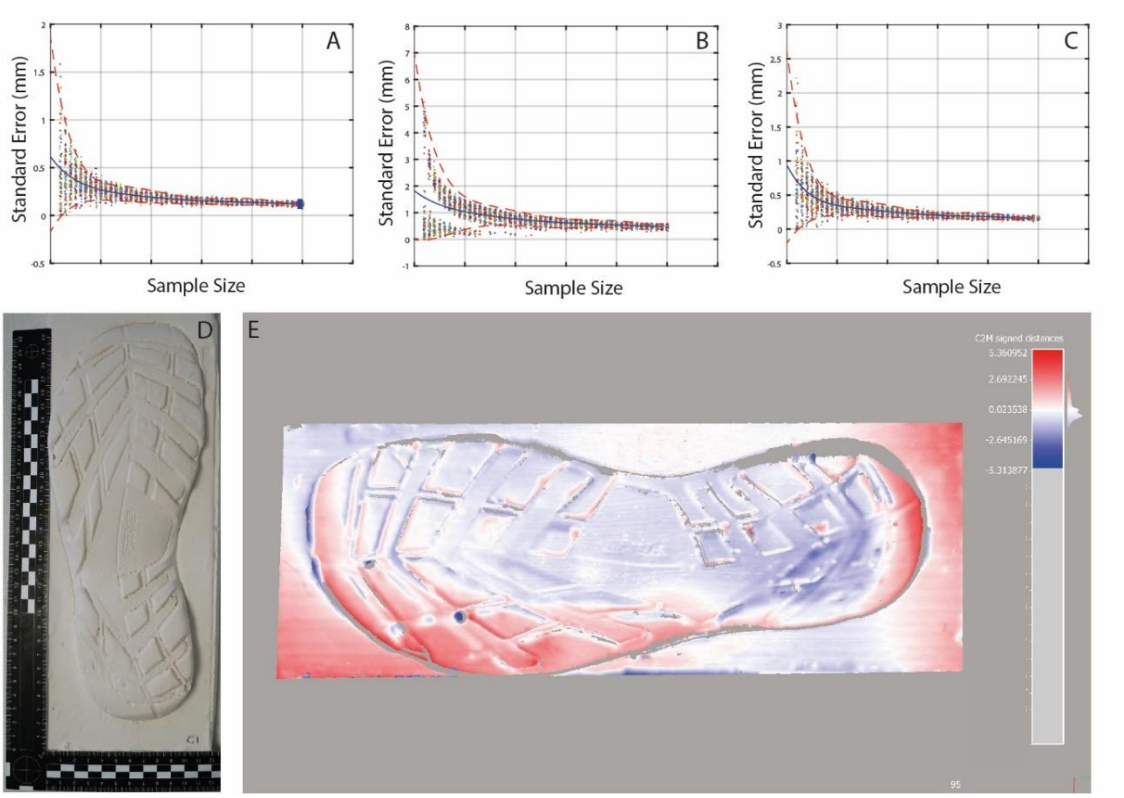

Figure 47. **A** Precision curve associated with Length measurement. **B** Precision curve associated with Width measurement. **C** Precision curve associated with Known Point measurement. **D** Example photograph of cast number 1. **E** CloudCompare comparison output of Cast 2 and Cast 11, note the air bubble in dark blue highlighting the highest area of disparity between casts.

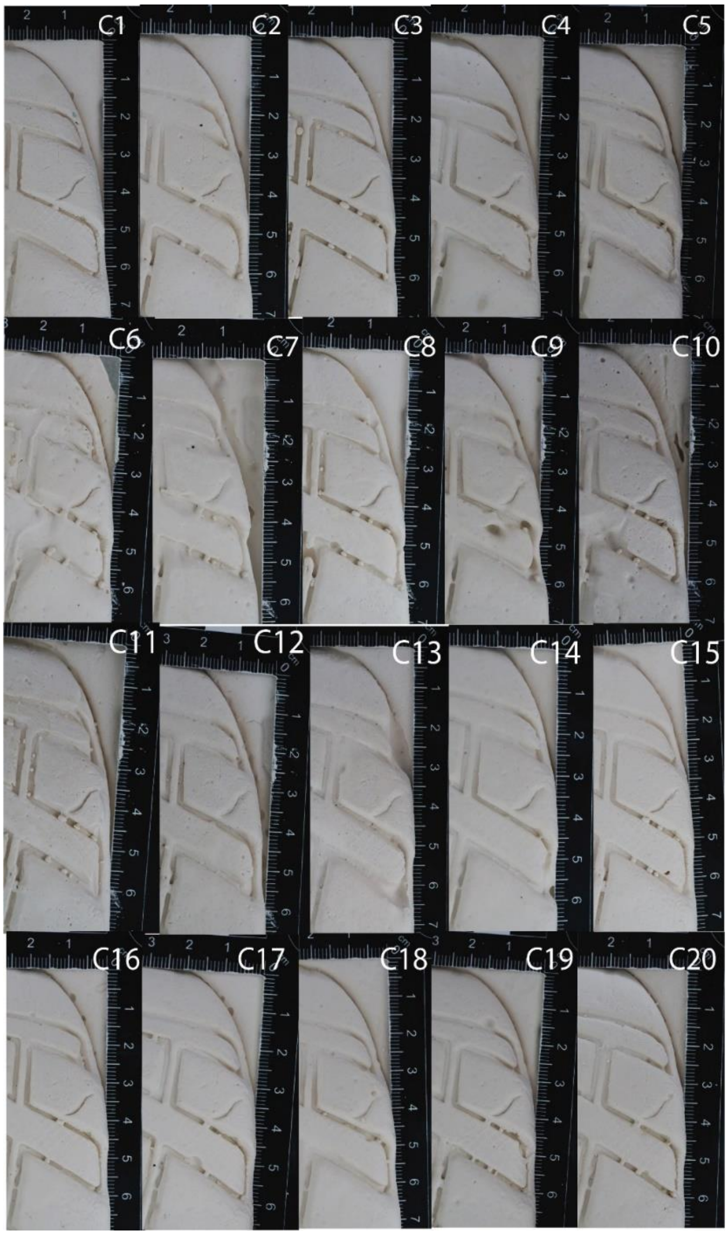

Figure 48. Photographs of part of all 20 casts showing a prominent RAC.

Discussion

The results reported here provide a first order estimate of the reproducibility and associated errors with conventional casting of footwear evidence. Basic dimensions are reproducible with low levels of error. The worst case is for length measurements which would need to be greater than 5.9 mm difference to be statistically significant at 95%. Given that the size between shoe sizes is 8.46mm this is potentially significant, but errors are not as marked in other dimensions. Class characteristics are also well reproduced in all the casts and there would be little question of the shoe type being identified, and broad wear characteristics identified, for example around the heel and forefoot. The close-up images of the outsole area with a prominent RAC show much greater small-scale variability between the casts, with occasional casts introducing artefacts into the impression changing the dimension of some of the treads and inter-tread areas. Perhaps the most significant feature of many of the casts is the presence of small air pockets between the treads and this varies quiet markedly between casts. Air bubbles also cause some pitting of the surface of some of the treads in some of the casts. It is possible that these could be mistaken for stones and lodged debris between treads, they also potentially introduce an element of uncertainty around features in these areas. Bubbles are a fact of life with most casting processes, they can minimise in the laboratory by using vacuum pots to extract air, but practically in the field this is not going to be possible. Careful mixing to avoid introducing air into the mix is something which is rarely stressed in the practical manuals but needs to be considered. The flexibility of the silicone mould itself may also be partially responsible for the variability between casts. A limitation of this study is the use of only one mould material, an area for further research would therefore be the repetition of this experiment using different mould materials, for example, a firm inflexible material. This may create difficulties in removing the cast from the mould but should be explored nonetheless.

The issues associated with casting lie not with the accuracy of the method but with the time it takes for the process to be undertaken, especially in a damp or humid climate where setting times for dental stone can be more prolonged. Casts are also bulky to store and difficult to measure digitally and compare to other traces using digital overlay methods. It is these operational differences that probably favour alternative digital techniques such as optical laser scanning or the application of some form of SfM photogrammetry.

Conclusion

Casting forensic footwear evidence is part of the traditional CSI toolkit and has not changed appreciably over time since it was first introduced, except for better materials and the use of fixative sprays (Bodziak 2017). Despite this, there have been few attempts to quantify the accuracy and precision of such methods despite a growing emphasis on error rates and precision within forensic science more generally. This paper is one of the first to attempt to quantify the precision of casting and establish the likely error rates. As such the results are surprisingly reassuring, demonstrating that in terms of gross size measurements, casts are reliable and precision high. What this work does illustrate, however, is that in considering detailed small scale RACs and the like there is the potential for issues of precision to influence interpretations, although experienced footwear experts are likely to be aware of such issues.

While other disciplines, such as palaeontology and archaeology, focused on the recovery of trace evidence have switched almost exclusively to the use of digital methods the drive to do so in forensic footwear should not be justified on issues of precision and accuracy but more based on the advantage for statistical analysis, visualisation, storage and data sharing.

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