3D-Printed Footwear Impressions as a Tool for Simulation-Based Forensic Education

Veronika Kollová[1,*] and Lukáš Lencsés[1] and Eduard Kolla[2]

[1] Faculty of Security Engineering, University of Žilina, Univerzitná 8215/1, 010 26 Žilina
[2] Institute of Forensic Research and Education, University of Žilina, Univerzitná 8215/1, 01026 Žilina
*veronika.adamova@uniza.sk

Abstract. Three-dimensional printing provides new possibilities for transforming digital forensic data into physical models that can be repeatedly examined, analysed, and used in practical training. This paper focuses on the application of 3D printing to the reproduction of three-dimensional footwear impression evidence and explores the potential use of such replicas in simulation-based forensic science education. A digital model of a footwear impression was prepared for physical reproduction using two additive manufacturing approaches: fused deposition modeling (FDM) and stereolithography (SLA). The workflow included preparation of the digital model, slicing, printing, and post-processing of the resulting replicas. Particular attention was paid to the practical requirements and limitations of both printing approaches. Under the tested conditions, the exploratory observations indicated that SLA printing considerably reduced the production time of the tested footwear impression model compared with the previously applied FDM approach, while requiring additional procedures related to model preparation, cleaning, and UV curing. The results also highlighted the importance of appropriate print settings, support structures, and material selection when reproducing geometrically complex forensic traces. From an educational perspective, 3D-printed traces from simulated crime scene replicas are proposed as reusable physical objects that can be incorporated into simulated scenarios and practical tasks focused on trace documentation, measurement, comparison, and interpretation. The presented approach therefore provides a connection between digital documentation, physical replication, and simulation-based practical education.

Keywords: 3D Printing, Footwear Impressions, Forensic Science, Simulation-Based Education.

1 Introduction

Technological development in **digitalisation, 3D documentation, and additive manufacturing** is expanding their application in forensic practice, particularly in the examination of physical traces requiring the capture, analysis, and reproduction of spatial and geometric characteristics. **Footwear impressions represent an important category of trace evidence that may provide information relevant** to class and, in

© The Author(s) 2026
K. Hollá et al. (eds.), *Proceedings of the SAFAR Scientific Conference 2026 – Building Awareness Through Immersive Learning (SSC-BAIL 2026)*, Atlantis Highlights in Social Sciences, Education and Humanities 57, https://doi.org/10.2991/978-94-6239-817-7_13

some cases, individual identification [1]. Previous studies by the authors have focused on their 3D documentation using laser scanning and photogrammetry, as well as on the accuracy and applicability of the resulting digital models [2, 3, 4]. Related research at the authors' institution also includes the creation of reference impressions and their further processing using 3D technologies [4, 5].

A further step in this workflow is the transformation of a digital model into a physical replica using 3D printing. Such replicas can be handled, measured, and incorporated into experimental or practical tasks. **The aim of this paper is to demonstrate the application of 3D printing to the reproduction of footwear impressions and to explore the potential use of the resulting physical replicas in simulation-based forensic science education.** The practical part is based on the reproduction of an existing digital footwear impression model using SLA technology [6].

At the same time, **the paper highlights the opportunity for students at the Faculty of Security Engineering, University of Žilina, to work directly with 3D printing technologies** and apply them to selected research and practical problems in the field of security. In this context, 3D-printed forensic replicas provide a practical link between **research activities, technology-enhanced education, and simulation-based forensic training.**

1.1 Theoretical Background – Footwear Impressions

Footwear impressions represent a significant source of forensically relevant information. According to their formation mechanism, they can be classified **as two-dimensional (2D) and three-dimensional (3D or plastic) impressions** (see Fig. 1).



Fig. 1. Examples of three-dimensional footwear impressions in soil with different grain sizes [7].

While two-dimensional footwear impressions primarily record outsole characteristics in a single plane, three-dimensional impressions are formed in deformable substrates such as soil, sand, or snow and preserve depth and other spatial features [1]. Footwear impressions may contain both class characteristics, including outsole type, size, and tread pattern, and individual characteristics resulting from wear or damage [1]. Traditionally, such impressions are documented or recovered using photography,

casting, or securing the original substrate [1]. For three-dimensional impressions, however, preservation of their spatial geometry, including depth and volume, is particularly important.

The increasing use of **3D scanning and photogrammetry** provides additional possibilities for capturing these characteristics [8, 9]. Previous studies by the authors have focused on the accuracy and applicability of these technologies for documenting three-dimensional footwear impressions [3, 4]. In the present research context, 3D documentation is considered part of a broader workflow comprising **spatial data acquisition, digital model generation, analysis, and physical reproduction** [10]. This approach builds on previous work at the authors' institution combining 3D scanning, photogrammetry, and 3D printing in footwear impression research [4, 5].

1.2 Theoretical Background – 3D Printing

3D printing, or additive manufacturing, creates a physical object from a digital model by depositing or curing material layer by layer [6]. Before printing, the model is processed in slicing software, which divides it into individual layers and generates the instructions required by the printer.

The technologies relevant to this study are **Fused Deposition Modelling (FDM)** and **Stereolithography (SLA)**. FDM deposits heated thermoplastic filament through a nozzle, whereas SLA cures liquid photopolymer resin using ultraviolet radiation [6]. The two technologies differ in material, model preparation, printing parameters, and post-processing requirements, which may affect the detail and quality of the resulting replica [6].

In forensic applications, 3D printing enables digital models to be converted into tangible replicas for examination, visualisation, interpretation, and presentation [10, 12, 13]. **The quality and dimensional fidelity of such replicas depend on the complete workflow**, including the original 3D data, model preparation, printing technology, material, layer thickness, orientation, and post-processing [6, 11, 12]. Accordingly, their forensic use requires awareness of technological limitations and appropriate methodological validation.

2 Practical Reproduction of a Footwear Impression Using 3D Printing

The practical part of this paper focuses on the physical reproduction of a three-dimensional footwear impression from an existing digital model. This part of the paper is based on the processing of a diploma thesis [6] completed at the Faculty of Security Engineering, University of Žilina. **The aim is to examine a complete workflow in which digitally documented footwear impression evidence is prepared for additive manufacturing and subsequently reproduced as a tangible physical replica.** The

procedure builds on previous work [14] in which a footwear impression was captured photogrammetrically and reproduced using FDM technology, while the present experiment extends this approach through the application of **SLA printing** [6].

The use of SLA was selected primarily to examine whether this technology could provide a more time-efficient alternative for reproducing geometrically complex footwear impressions while maintaining sufficient surface detail. At the same time, the experiment was intended to explore practical limitations associated with model preparation, printing orientation, support structures, material consumption, and post-processing. Particular attention was therefore paid not only to the final print, but also to the individual stages of the printing workflow and to the technical problems encountered during reproduction.

According to [6], the practical experiment thus serves two exploratory purposes:

- to explore the feasibility of converting a digital footwear impression model into a physical replica using SLA technology,
- to provide a basis for comparison with the previously applied FDM workflow in terms of printing procedure, production time, and practical requirements.

2.1 Materials and Methods

An existing **digital 3D model of a three-dimensional footwear impression** (see Fig. 2), created as part of previous research focused on photogrammetric documentation and 3D reproduction of footwear impressions, was used for the experiment, a more detailed description of the model creation workflow is provided in [14]. The model was processed and modified using **Agisoft Metashape, Meshmixer, and Autodesk Tinkercad** [6, 14].

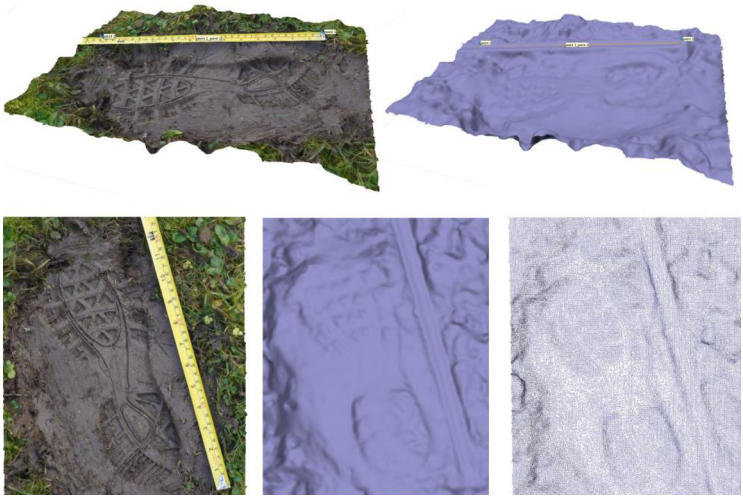


Fig. 2. 3D model of a footwear impression [14].

SLA printing of the footwear impression

For the physical reproduction of the impression, SLA technology was selected using a **Phrozen Sonic Mighty 8K** (see Table 1). **Phrozen Speed Resin** was used as the printing material (see Table 2).

Table 1. Technical specifications of the Phrozen Sonic Mighty 8K 3D printer [15].

Parameters	Description
Printing resolution	8K resolution with a pixel size of 28 μm
Build volume	218 x 123 x 235 mm
LCD screen	10-inch monochrome with an estimated service life of up to 2 000 operating hours
Light source	LED module with linear projection technology
Motion system	Dual linear rail system ensuring improved stability and precision during printing
Remote monitoring	Real-time monitoring and control via smartphone
Connectivity	USB interface and wireless control via WLAN
Control interface	5-inch touchscreen display
Printer dimensions	337 × 337 × 516 mm
Printer weight	14.3 kg

Table 2. Parameters of the Phrozen Speed Resin [16].

Parameters		Standard	Typical values
General properties	Appearance	-	Grey
	Viscosity (BROOKFIELD, LV)	-	165 - 250 cps
	Density (liquid resin)	ASTM D4052-18a	1.13 g/cm³
Mechanical properties	Tensile strength at break	ASTM D638	45.5 MPa
	Tensile modulus	ASTM D638	3019.7 MPa
	Elongation at break	ASTM D638	12.9 %
Impact properties	Izod impact strength	ASTM D256	34.1 J/m
Thermal properties	HDT (0.45 MPa)	ASTM D648	59.3 °C
Hardness	Shore D hardness	ASTM D2240	75-80D

The digital model was **iteratively modified during the preparation and printing process** in response to the technical requirements identified during individual printing attempts. Two slicing software packages were therefore used: **Lychee Slicer**, which was applied during the initial preparation of the model, and subsequently **ChituBox Basic**, which enabled further modification of the model, including hollowing, adjustment of the internal structure, creation of drainage holes, and optimisation of support structures. The software interfaces are shown in Fig. 3.

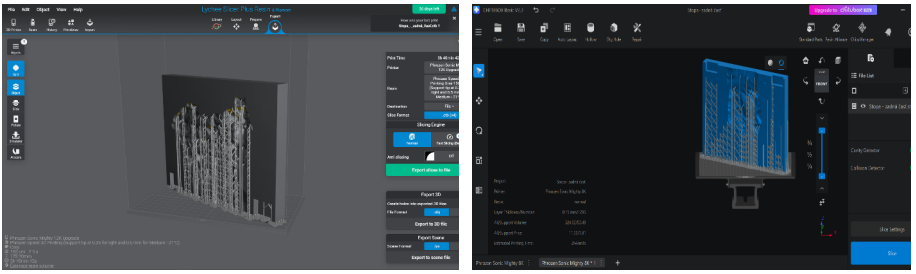


Fig. 3. Lychee slicer interface (left side) and ChituBox slicer interface (right side) [6].

Due to its dimensions, the model was divided into two parts, both of which were printed using the same parameters. A layer thickness of **150 µm** was selected (**compared with FDM printing, SLA allows the use of much thinner layers, enabling a higher level of detail in the printed model**). The methodological procedure included model preparation, generation of support structures, SLA printing (see Table 3), removal of the printed model from the build platform, cleaning, drying, and UV curing (see Fig. 4).

Table 3. Optimal SLA printing settings for the footwear impression [6].

Parameter	Specification	Parameter	Specification
Number of layers	6	Lift speed (2)	60 > 240 mm/min
Exposure time (1)	22 s	Retract speed (2)	150 > 120 mm/min
Number of transition layers	6	Wait before print	1 s
Lift distance	8 > 4 mm	Wait after print	0 s
Retract distance	9 > 3 mm	Wait after lift	2 s
Lift speed (1)	60 > 240 mm/min	Light intensity	100 %
Retract speed (1)	240 > 60 mm/min	X scale	100 %
Light intensity	100 %	Y scale	100 %
Layer thickness	150 µm	Z scale	100 %
Exposure time (2)	2.5 s	Layer curing time	42 s
Lift distance	8 > 4 mm	Time per layer	11.1 s
Retract distance	11 > 1 mm		

After printing, the models were cleaned in isopropyl alcohol, subsequently dried for approximately 30 min, and then UV-cured for an additional 30 min (see Fig. 4). When handling the resin, personal protective equipment including nitrile gloves, respiratory protection, and safety glasses was used. The experiment demonstrated the **technical feasibility of reproducing a three-dimensional footwear impression using SLA printing**. It also highlighted the importance of appropriate **model preparation, support structures, sufficient resin supply, and post-processing**, particularly when printing larger and geometrically complex models.



Fig. 4. Demonstration of printing and curing the 3D model of the footwear impression [6].

FDM printing of the footwear impression

The reproduction of the footwear impression using FDM was carried out as part of previous research. The workflow included photogrammetric documentation of the footwear impression, generation and preparation of the digital 3D model, and its subsequent reproduction using FDM technology. A simplified overview of this process is shown in Fig. 5. The printing parameters used for the FDM reproduction are summarised in Table 4. The build plate temperature was set to 60 °C, the nozzle temperature to 200 °C, and the printing speed to 60 mm/s. A layer height of 0.12 mm was used. Additional brim structures were applied to improve adhesion to the build plate, while the cooling fan operated at 100%.

Table 4. FDM printing settings for the footwear impression [6].

Parameter	Specification
Build plate temperature	60 °C
Nozzle temperature	200 °C
Printing speed	60 mm/s
Layer height	0.12 mm
Build plate adhesion	Brim added
Fan speed	100 %

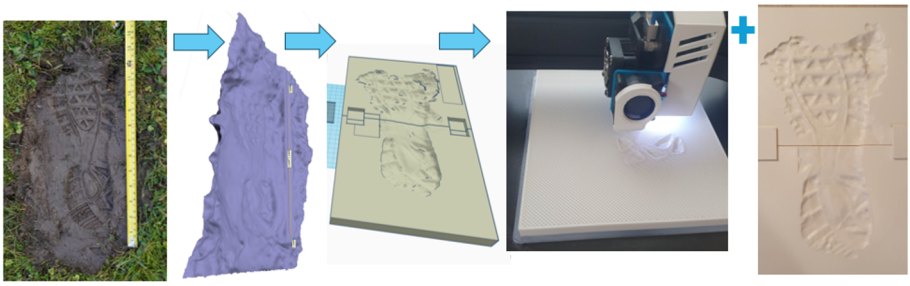


Fig. 5. Workflow for photogrammetric documentation of the footwear impression and subsequent FDM printing [6].

2.2 Results

The resulting 3D-printed footwear impression replicas were subsequently assessed by a forensic technician from the Criminal Police of the Police Force of the Slovak Republic. The expert assessment (further information is provided in the thesis [6]) provided a practical perspective on the usability of the produced replicas in forensic applications. In the context of the works [6, 14], these replicas are proposed as reusable training objects in simulation-based forensic science education, their educational effectiveness was not empirically evaluated with students or teachers. The successfully printed sections obtained after optimisation are shown in Fig. 6.

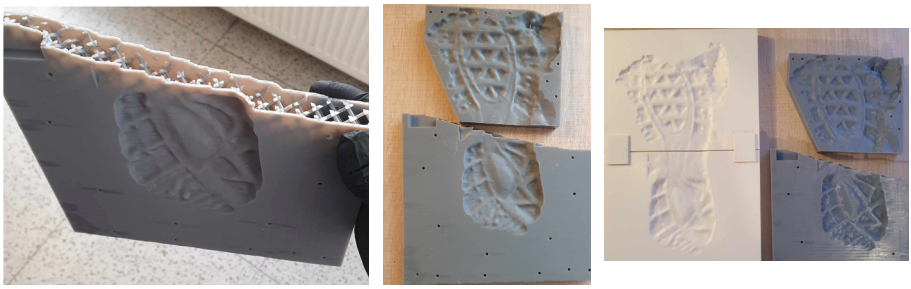


Fig. 6. 3D Model of a footwear impression printed using SLA technology and comparison of footwear impression prints produced using FDM (white model) and SLA (grey model) technologies [6].

3 Conclusion

The presented study provides exploratory observations on the feasibility of using 3D printing to reproduce three-dimensional footwear impressions and their potential for both forensic applications and simulation-based education. An existing digital 3D

model of a footwear impression was reproduced using FDM and SLA technologies, linking digital documentation with physical replication.

The observations indicate that **successful SLA reproduction is influenced by appropriate model preparation, support structures, hollowing, drainage, printing parameters, and post-processing**. Under the tested conditions, SLA was substantially more time-efficient than the previously applied FDM workflow: printing a comparable section required approximately **4 hours using SLA compared with 34 hours using FDM**, although SLA additionally required cleaning, drying, and UV curing. The resulting prints were also assessed from the perspective of forensic practice. These findings emphasise the need for further validation and **standardisation of the complete digital-to-physical workflow before its broader forensic application.**

Beyond forensic practice, **3D-printed footwear impression replicas are proposed as reusable objects for practical and simulation-based forensic science education**. They could be incorporated into simulated crime scenes and tasks involving documentation, measurement, comparison, and interpretation, while the same digital model could be repeatedly reproduced for different groups of students. The approach could also enable students to engage directly with the process from digital model preparation to physical printing, thereby linking **research, technology-enhanced education, and simulation-based forensic training.**

Acknowledgment

This paper was funded by: VEGA No. 1/0775/24: *Increasing the accuracy of 3D trace documentation for the purposes of forensic-technical and expert activities.*

References

1. Svítková, M., et al.: Trasológia – Stopy na mieste činu. 1st edn. Kriminalistický a expertízny ústav Policajného zboru, Bratislava (2020).
2. Adamová, V., Kubjatko, T., Boc, K.: Možnosti využitia 3D snímacej technológie v kriminalistike. Trilobit 2/2019 (2019).
3. Adamová, V., Šoltés, V., Boc, K.: Dokumentácia trojrozmerných trasologických stôp pomocou aplikácie fotogrametrie blízkeho dosahu. Krízový manažment 21(1), 5–15 (2022). doi:10.26552/krm.C.2022.1.5-15.
4. Adamová, V., Kolla, E., Szabo, L.: Experimentálne verifikačné merania zamerané na posúdenie presnosti 3D dokumentácie trasologických stôp. Krízový manažment 24(1), 53–63 (2025). doi:10.26552/krm.C.2025.1.53-63.
5. Adamová, V., Kampová, K., Gajdošíková, T.: The Student as Researcher: A Model of Integrating Students into Scientific Work Through Grant-Funded Projects in the Field of Forensic Sciences. In: ICERI2025 Proceedings, pp. 6807–6817. IATED (2025). doi:10.21125/iceri.2025.1864.

6. Žiak, J.: Aplikácia 3D tlače na vybrané praktické a výskumné problémy kriminalistického skúmania. Master's thesis, University of Žilina, Faculty of Security Engineering, Žilina (2025).
7. Vrecko, R.: Analýza vplyvu vlastností podložia na morfológiu objemových stôp obuvi. Master's thesis, University of Žilina, Faculty of Security Engineering, Žilina (2026).
8. Galanakis, G., Zabulis, X., Evdaimon, T., Fikenscher, S.-E., Allertseder, S., Tsikrika, T., Vrochidis, S.: A study of 3D digitisation modalities for crime scene investigation. Forensic Sciences 1(2), 56–85 (2021). doi:10.3390/forensicsci1020008.
9. Ospina-Bohórquez, A., Del Pozo, S., Courtenay, L.A., González-Aguilera, D.: Handheld stereo photogrammetry applied to crime scene analysis. Measurement 216, 112861 (2023). doi:10.1016/j.measurement.2023.112861.
10. Carew, R.M., French, J., Morgan, R.M.: 3D forensic science: A new field integrating 3D imaging and 3D printing in crime reconstruction. Forensic Science International: Synergy 3, 100205 (2021). doi:10.1016/j.fsisyn.2021.100205.
11. Abdelaal, O., Aldahash, S.A.: Realization of Impression Evidence with Reverse Engineering and Additive Manufacturing. Applied Sciences 14(13), 5444 (2024). doi:10.3390/app14135444.
12. Errickson, D., Carew, R.M., Collings, A.J., Biggs, M.J.P., Haig, P., O'Hora, H., Marsh, N., Roberts, J.: A survey of case studies on the use of forensic three-dimensional printing in England and Wales. International Journal of Legal Medicine 136, 1605–1619 (2022). doi:10.1007/s00414-022-02872-4.
13. Jani, G., Johnson, A., Marques, J., Franco, A.: Three-dimensional (3D) printing in forensic science – An emerging technology in India. Annals of 3D Printed Medicine 1, 100006 (2021). doi: 1016/j.stlm.2021.100006.
14. Žiak, J.: 3D tlač v kriminalistike. Bachelor's thesis, University of Žilina, Faculty of Security Engineering, Žilina (2023).
15. 3DJAKE: *Phrozen Sonic Mighty 8K* (2026). https://www.3djake.sk/phrozen/sonic-mighty-8k, last accessed 2026/09/07.
16. 3DJAKE: *Phrozen Resin User Guide – Phrozen Speed, Gray* (2025). https://3d.nice-cdn.com/upload/file/User_Guide_Speed_Resin_Gray_EN_V4.pdf, last accessed 2025/04/07.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (http://creativecommons.org/licenses/by-nc/4.0/), which permits any noncommercial use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

