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(Im)material Casts from the Sullan Period †

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Abstract: Thanks to Pompeii's burial under Vesuvio's 79 AD eruption deposits, the ballistic imprints on its northern defensive perimeter are uniquely attributable to Sulla's siege of 89 BC. These impact marks were digitally documented using integrated survey techniques and custom pipelines. The virtual casts generated—dimensionally accurate, high-resolution surface replicas—serve as key inputs for the reverse-modeling of damage craters, supporting terminal ballistics analyses. Two case studies—a stone projectile cavity and fan-shaped dart impressions—were 3D-printed at 1:1 scale. Prototype casting thus emerges as a cultural asset and rapidly updatable component of a dynamic data ecosystem, inclusive of users with disabilities.

Keywords: 3D printing; accessibility; ballistic imprints; digital heritage; elastic torsion launcher; life-size printing; Sulla's siege; rapid prototyping; reverse modeling; virtual casts

1. Introduction

Handling 3D-printed digital casts—prototypes of the ballistic imprints discovered along the perimeter of ancient Pompeii [1]—is striking. Although removed from their original context, the casts reveal the surface roughness and dimensions that evoke the force of impact, recalling the dramatic descriptions by Titus Flavius Josephus, who witnessed the Siege of Jerusalem in 70 AD [2].

The artillery employed on that occasion was essentially identical to that used by Lucius Cornelius Sulla when he took Pompeii in 89 BC [3]. The surviving stretch of wall, preserved beneath volcanic deposits from the 79 AD eruption and only excavated in the early twentieth century, now stands as the sole definitive evidence of the lethal capabilities of ballistae and catapults before Christ; the craters in the stone ashlars, caused by the violent impacts of limestone spherical projectiles and metallic arrows (Figure 1), cannot be mistaken for damage sustained during World War II bombings, which have been documented in detail [4].

Thus, confident in their secure dating, the direct examination of these cavities—grounded in foundational knowledge of Republican and Imperial poliorcetics—allows us to identify features that, despite ancient restorations and a century of atmospheric exposure, form the basis for sizing elastic torsion launchers, of which only a few fragmentary remains exist [5,6].

The design principles outlined by Philo of Byzantium (*Belopoeica*, 3rd century BC) and later codified by Vitruvius in Book X of *De Architectura* (1st century AD) enable the calculation of siege engine components according to a standard module (Figure 2a,b)—the side of the "modiolus" (little module) equals the diameter of the flanges that secure the

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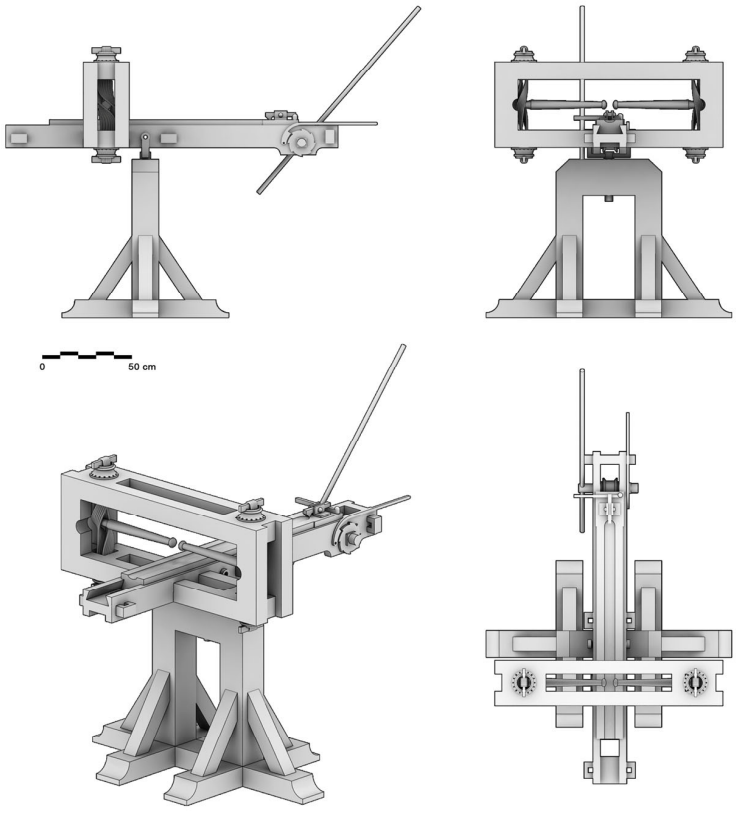
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elastic bundles to the frame, a dimension from which ancient authors derived weapon power [7].

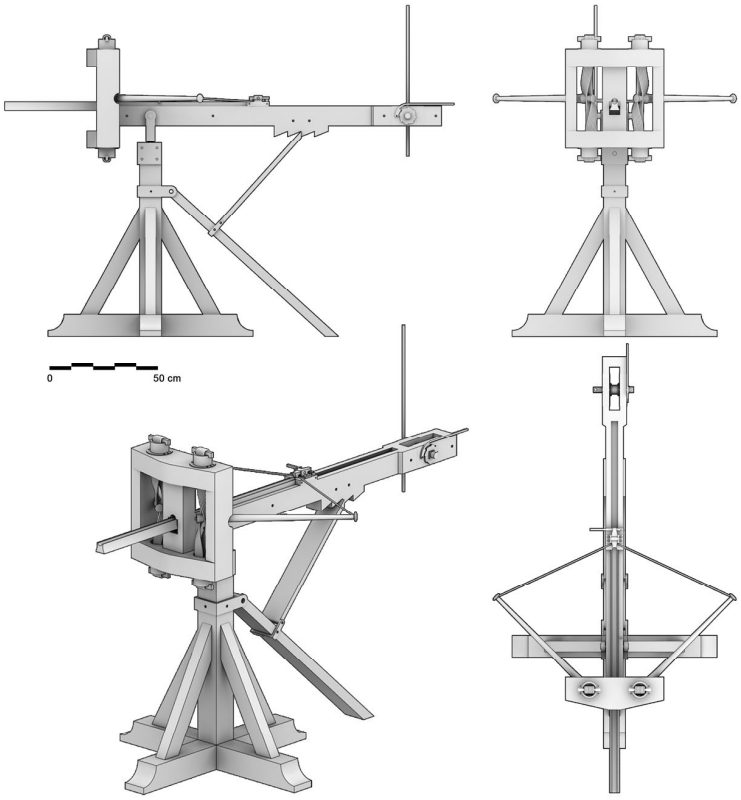


Figure 1. Images of the ballistic imprints (circular marks caused by stone projectiles) visible on the northern city walls of Pompeii. Photo 2016 (MIBACT-SSBA-PES PROTO-ARCH 0006225 14 April 2016 CI. 28.13.07/6).



(**a**)

Figure 2. *Cont.*



(**b**)

Figure 2. Orthographic and axonometric views of the 3D model of a Roman weapon: (**a**) ballista; (**b**) scorpion. Models by C.F.

By measuring the bundle diameter, one can obtain firing parameters that can subsequently be partially validated through reverse engineering processes (Figure 3).

The digital process used to capture and reconstruct the virtual casts, which are subsequently prototyped, integrates phases that are traditionally separate. Cyclic and interactive processes of analysis and synthesis follow one another within a single pipeline for data acquisition. These processes yield a collection of information useful for transferring content and fostering collaboration through Information and Communications Technology (ICT). Sharing these ontological structures provides users with informational platforms and (im)material spaces [8] suitable for expanding their perceptual boundaries (Mixed Reality, MR). By introducing digital elements, advanced technologies promote not only visual inclusion but also the cognitive inclusion of users (Extended Reality, XR). It is therefore necessary to reconcile, on the same surveyed and processed models, the precision and accuracy required for documentation and study with the exemplification demanded by the sharing of results in progress and for future reference. Dedicated and interoperable platforms (Common Data Environment, CDE) widely engage users, facilitating access to resources for educational, social, and economic programs.

The primary question this paper seeks to address concerns a critical phase of the unique, cyclical and interactive process—the physical prototyping of digital casts selected as case studies, which represents a significant mode of operation and serves as a an opportunity for cultural exchange between research, education and the so-called Third Mission.

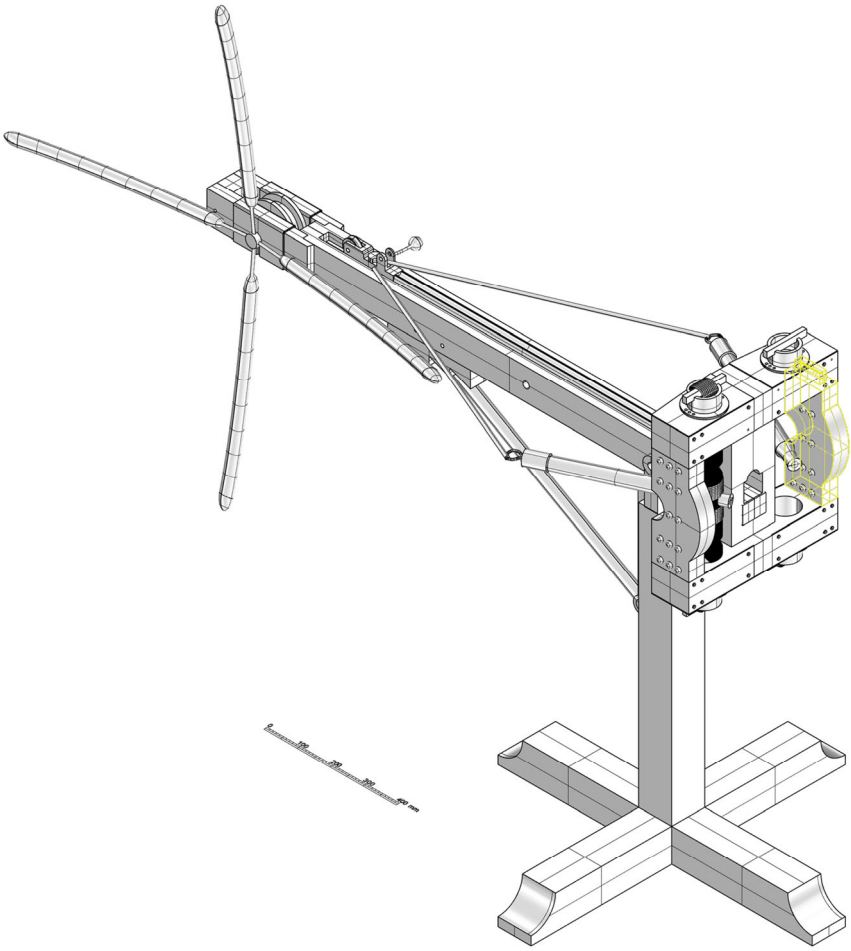


Figure 3. An axonometric view of the 3D model of a Roman weapon, called the *scorpio*. Model and rendering by C.F.

2. Materials and Methods

This research is based on graphic outputs derived from visual representations designed to produce digitally accessible content. Both expressive and conceptual—whether iconic or symbolic, survey- or design-based—the graphic results reflect an experience in which apparent antinomies dissolve into action, illustrating the interplay between existing work and future planning. As Migliari (2004) observes [9], it is appropriate to provide the term "drawing" with wider connotations, to encompass the notion of "model". It is certainly a model, as the prototype casts are derived from reality-based 3D processing. The process is a recording of the physical world as it appears at the moment of capture [10].

The output of post-processing operations on point clouds acquired with active and passive sensors are models consisting of polygonal meshes. Exported at resolutions appropriate to their purpose, and free of holes or topological defects, these 3D models are adaptable to various applications, including effective dissemination via 3D printing.

Photogrammetric reconstructions using Structure from Motion (SfM) precede the 3D prints of the impact case studies selected for the analysis. To preserve contextual integrity, the studied cavities were located in the approximately 300 m wall section between Vesuvio Gate and Ercolano Gate. This reference frame was necessary to locate the different elevations relative to the actual ground level and determine each projectile's angle of incidence on the ashlars and the resulting crater geometry. Such data are essential to the subsequent mechanical tests that intend to support terminal ballistics calculations.

The polygonal mesh documents impact features in high detail and in a complete way. When analyzed with dedicated software for automatic surface characterization, it yields geometric primitives that allow us to hypothesize, with reasonable confidence, the most plausible shapes of the studied impacts (reverse modeling, RM).

The Finite Element Method (FEM) and Finite Element Analysis (FEA) will then validate these hypotheses and determine the launching power of the elastic torsion launchers, starting from the most significant and well-preserved examples, chosen because of the high circularity of the profile, diameter size, and depth.

Digital casts, saved in STL format (Stereo Lithography or Standard Tessellation Language), are used to prototype object geometry without preserving color or texture information.

Digital casts—both the negative molds (inverted geometry) and their positive casts (replica geometry of the cavity)—are extracted generally without color texture in the appropriate format for printing, usually the Stereo Lithography or Standard Tessellation Language (STL), and used to materially replicate the geometry of the object.

The use of an analog, continuous model that extends into physical space "provides not only visual perception but also haptic feedback (from the Greek word for Touch), material scent of which it is composed, and acoustic resonance, sharply contrasting with purely digital processing" [11]. In this light, reliable 3D-printed copies of detailed digital casts confirm the advantages of historical maquettes based on technical drawings, even if they are not handmade with fine materials; beyond illustrating [12] (p. 117) or persuading patrons [13] (p. 40, 207), they can verify the structural behavior and coordination of each element [14] (I, pp. 860–862), that is, helping in studying extreme scales [15] (V, 18, p. 467) or guiding construction [16]. Prototyped models thus open up new opportunities [17].

In fact, 3D printing, while offering a choice, albeit a limited one, uses materials that are not perishable and limit cracking, deforming or shrinking over time, and they can be reprinted for purposes of reducing costs and time. In addition, since they derive from digital models, they enable real-time corrections and rapid, low-cost reprints. These rectifications and optimizations can support user inclusion [18]—with proper attention, they compensate for some physical deficits [19,20] or can extract features of real complexity suitable for the understanding and enjoyment for younger or differently abled children.

We therefore ask how and to what extent these case studies can advance the field. In the context wherein case studies serve not as trivial applications but as an opportunity for dialogue, it is crucial to direct acquisition projects that can capture exceptionally irregular surfaces, such as impact craters, and to derive an inverse model that closely approximates reality. Ensuring dimensional and geometric reliability is critical for the quality of the subsequent steps.

3. Results: Virtual Casts and Reverse Modeling

Two types of case studies were surveyed, and accordingly two examples were selected, as follows:

1. A cavity created by a stone projectile, together with its positive cast and the corresponding theoretical projectile (sphere), of which the maximum diameter was deduced from the cavity via geometric analysis of the surface (Figure 4);
2. A series of fan-shaped cavities, likely produced by metal-tipped darts, together with its positive cast and a reconstructed theoretical dart (frustum of a square pyramid), modeled on the proportions of a Roman-period example that is still preserved (Figure 5). Figure 6 illustrates the study of the arrow tip chosen for prototyping.

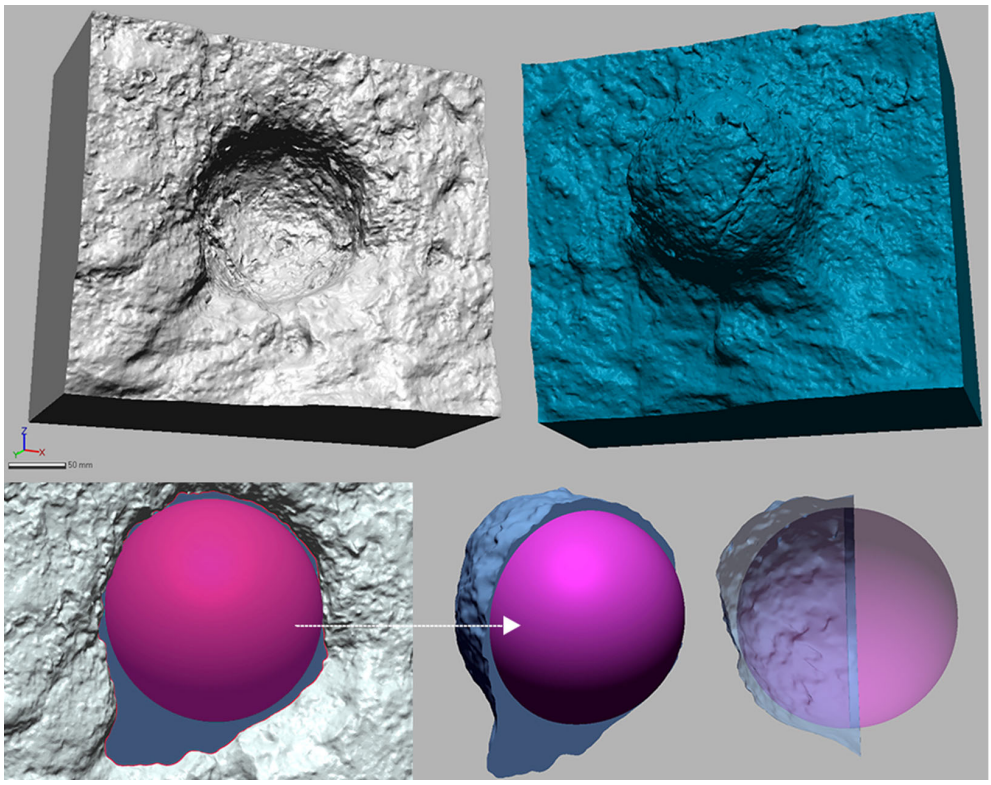


Figure 4. 3D models of the positive cast (**above left**) and the negative mold (**above right**) obtained from a reality-based 3D survey of the circular cavity, with a solid model of the theoretical spherical projectile that produced the impact (shown at **bottom**, **left** to **right**) and detail of the negative mold extrapolated from the ashlar (indicated by the arrow). Geometric analysis by S.B.

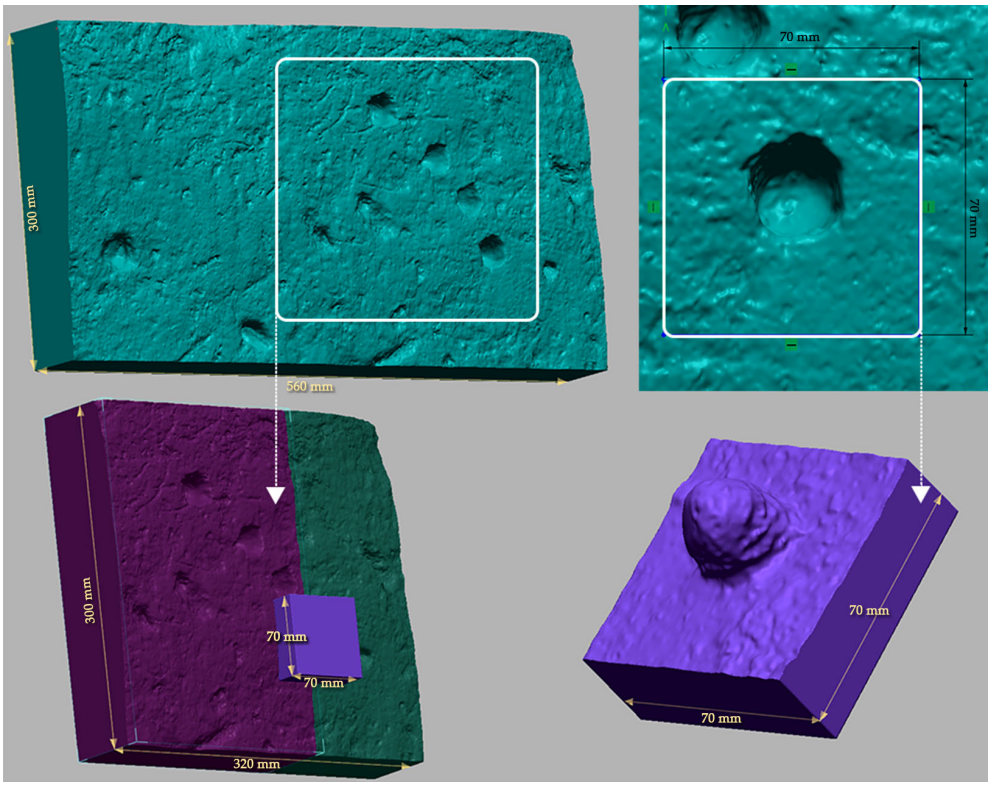


Figure 5. 3D digital models of a virtual cast of fan-shaped marks caused by metal arrowheads. The arrows indicate a close-up of the selected impact holes (left) and the depression from which the negative mold was extracted (left). 3D models and casts by S.B.

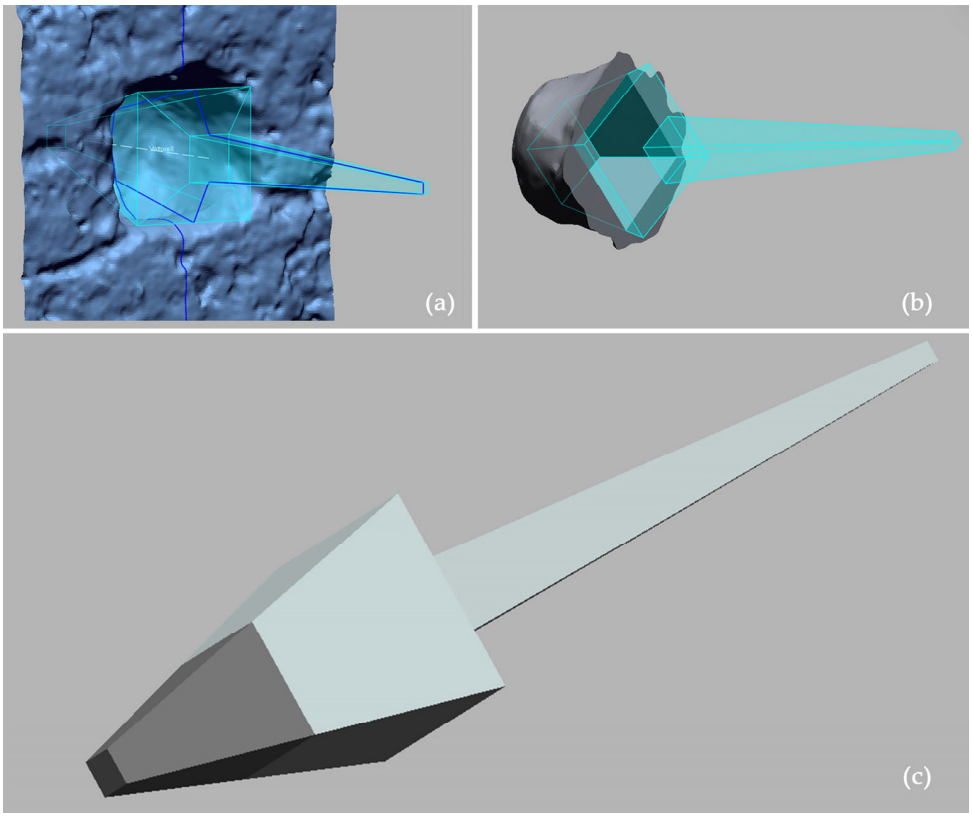


Figure 6. Experimental reconstruction of the metal arrow tip for prototyping, based on the geometry of the existing indentation (**a**,**b**) and the proportions of museum examples (**c**). Models by S.B.

For both examples, the high-resolution polygonal meshes of the impact craters were edited to close any holes and create a support platform. This platform was generated by Boolean operations (union, subtraction, or intersection) between the digital surface and a solid block, appropriately sized for single- or multi-part printing.

Several 3D-printing techniques [21,22] employ additive manufacturing with various materials and levels of detail. From an operational standpoint, the physical reproduction requires a geometry check: meshes must be watertight and manifold before printing. Since raw polygonal surfaces cannot be printed directly, models must be thickened and exported in a suitable format.

In order to prepare each cast model, we defined layer thickness, designed necessary supports, and arranged the nesting on the build plate. The process yielded smoothly finished pieces by printing the STL-converted models at 1:1 scale. We used an Anycubic Predator Fused Deposition Modeling (FDM) printer with PLA (Polylactic Acid) filament, set to a 0.2 mm layer height and 80 mm/s printing speed. Total print times are given in Table 1, and the final prints for both case studies are shown in Figures 7 and 8.

Printing at full scale and allowing later assembly—necessitated by complex overhangs, undercuts, protruding edges, and steep angles (or >45° to the build plate)—required dividing each cast into multiple magnet-joined segments (eight for the cavity cast, four for the mold, and five for the fan-shaped traces). This approach also resolved the challenge of reinserting the negative cast into its positive one, which would have been impossible with rigid material and without release-angle allowances.

Table 1. 3D prints of the case studies shown in Figure 7 (cases a and b) and Figure 8 (case f). 3D prints by C.F.

3D Print Settings	(Figure 7 Case a) Replica of Ballistic Impact	(Figure 7 Case b) Negative Mold	(Figure 8 Case f) Replica of Fan-Shaped Traces
Model scale	1:1	1:1	1:1
Model height	180 mm	180 mm	180 mm
Number of parts	8	4	5
Print layer thickness	0.2 mm	0.2 mm	0.2 mm
Infill percentage	10%	10%	10%
Infill pattern	grid	grid	grid
Estimated print time	50 h	32 h	21 h

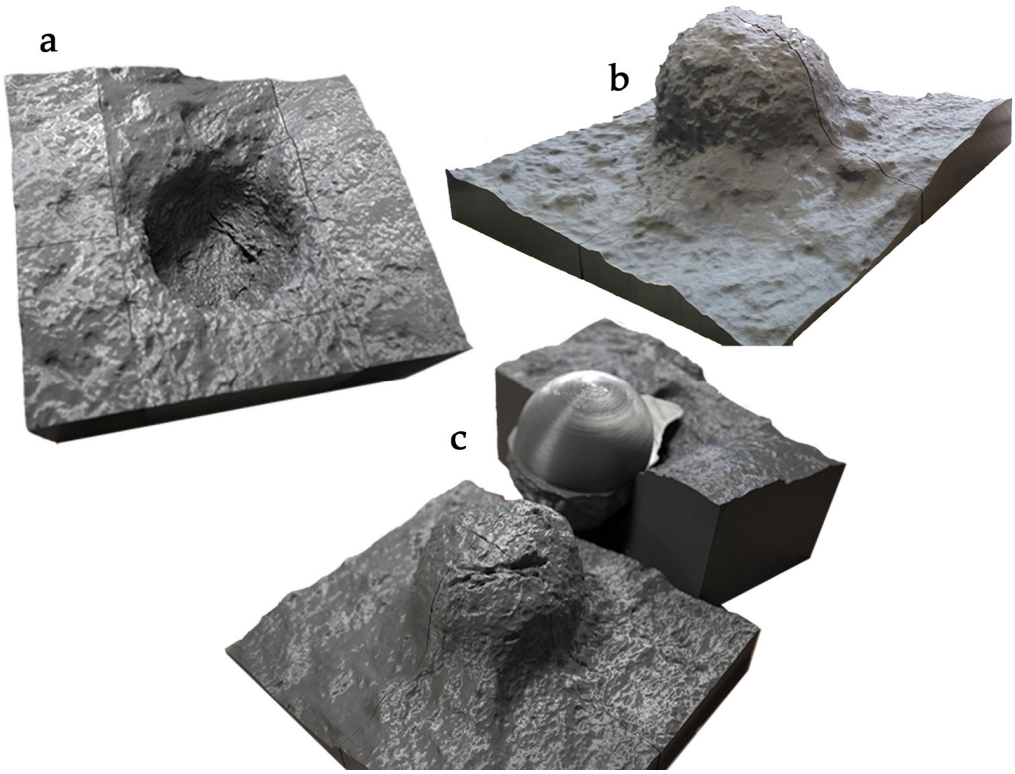


Figure 7. Prototyping of the two cavity types (stone projectiles): (**a**) replica of a ballistic impact based on the digital survey of the city walls; (**b**) negative mold; (**c**) theoretical spherical projectile. 3D-printed prototypes by C.F.

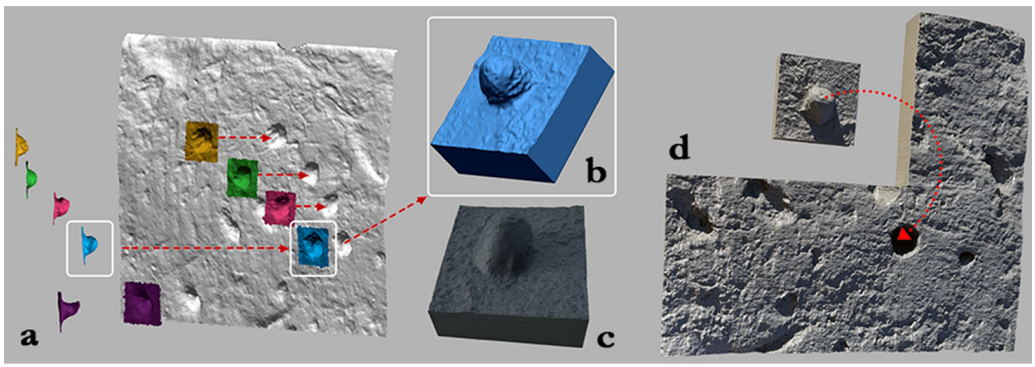


Figure 8. *Cont.*

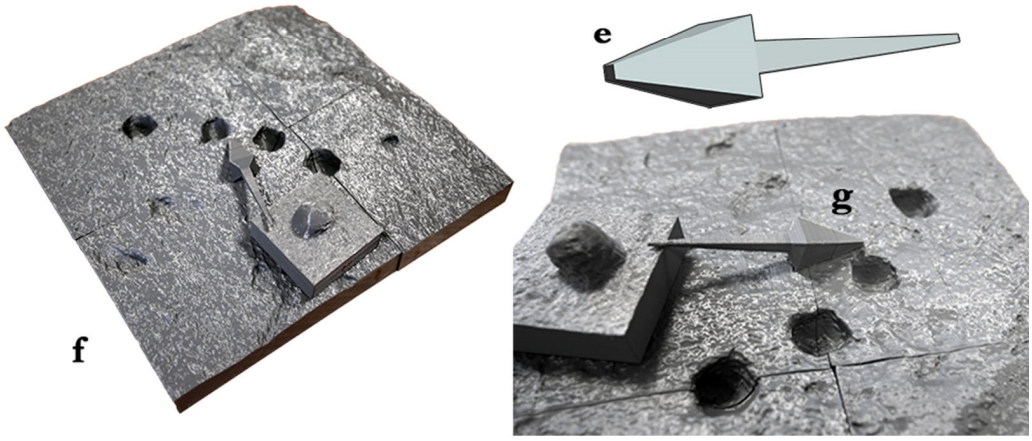


Figure 8. Prototyping of the two cavity types (darts): (**a**) digital survey of the fan-shaped dart marks; (**b**) virtual mold; (**c**,**d**) 3D-printed reproductions; (**e**) hypothetical digital dart model; (**f**,**g**) 3D prints of the fan-shaped dart cavities and metal arrow tip. Models by S.B.; 3D-printed prototypes by C.F.

4. Discussion

The physical 3D print of a digital model, like other representational forms, establishes an analogy with the original artifact despite being produced in different materials. As with its physical analog, the digital model records reality comprehensively through acquisition technologies (Range-Based Modeling (RBM) and Image-Based Modeling (IBM)) and modeling reconstruction techniques such as BIM—HBIM (Building Information Modeling). For practitioners versed in these tools, this approach yields a multifunctional artifact that integrates knowledge within a data-model ecosystem and supports subsequent heritage interventions.

The reliability of 3D models is certainly crucial. The optimization of workflows [23–25], driven by ongoing hardware and software developments, remains a topic of debate. Standardizing common formats for widely used applications [26], including photogrammetric ones based on SfM/MVS [27], seems more like a necessity than an opportunity for the scientific community involved in the documentation of historical and artistic heritage.

In this broad field of application of new technologies for cultural heritage, photogrammetry software based on computer vision processes has permeated multiple scales of documentation, providing effective solutions to diverse problems [28–30]. Integration into established pipelines has led to significant advancements in documentation, even in the architectural domain [31–38].

The digital model produced by integrating diverse acquisition methods provides the foundation for an artifact–knowledge pathway, within which rapid prototyping condenses key innovations. These advances lead to the development of new sectors in geometric modeling software as well as applications aimed at preparing 3D-printable files [39]. Like all additive technologies, fused deposition modeling works in layers, with the minimum layer thickness depending on various factors such as the machine's kinematics, the extrusion nozzle size, and the material used. Final prints must address surface imperfections, tolerance errors, anisotropy from layer orientation, and assembly challenges due to undercuts.

In the context of rapid development, limitations and opportunities must be carefully weighed. This is especially pertinent to recent advances in combining different representation techniques, such as the relation between traditional mesh surface representations and voxels. Voxels are novel units of a representation technique that associate volumetric pixels with the positions of a spatial grid. These volumetric pixels are numerical representations of volume and can be linked to properties such as color, opacity, material density, refractive index, position, force, time, velocity, and more.

As can be inferred, the voxel is a flexibly manipulable element that 3D printing can visualize to some extent by rendering the spatial grid in three dimensions. However, ongoing efforts aim to go further by enabling the accurate printing of voxels along with all their associated properties, to create increasingly complex materials with intrinsic characteristics—an approach often referred to as 4D printing.

Remaining within the field of 3D printing, the experiments presented—like any additive technology—highlight the challenges associated with printing carved or bas-relief works, namely, the indentations on the rough outer surface where the walls form a dihedral angle smaller than a right angle, known as undercuts.

5. Conclusions

The process makes use of digital methodologies that have now become established practices. The need for an acquisition strategy capable of ensuring the resolution required to faithfully reproduce rough cavities—sometimes consisting of holes just a few centimeters deep—represents a case study of interest, and paves the way for future developments. Central to the unified process, which links data acquisition, analysis, and dissemination within a single workflow, is the question this article seeks to address. The case study serves as a means to reflect on the cultural value of prototyping digital casts, highlighting how the printing of 3D models represents a significant mode of operation within a unique, cyclical, and interactive process that connects research, education, and the Third Mission.

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Abbreviations

The following abbreviations are used in this manuscript:

3D	Three-Dimensional
BIM/HBIM	Building Information Modeling/Heritage Building Information Modeling
CDE	Common Data Environment
FEA	Finite Element Analysis

FDM	Fused Deposition Modeling
FEM	Finite Element Method
IBM	Range-Based Modeling
ICT	Information and Communications Technology
MR	Mixed Reality
RM	Reverse Modeling
PLA	Polylactic Acid
RBM	Range-Based Modeling
SfM	Structure from Motion
STL	Stereo Lithography or Standard Tessellation Language
XR	Extended Reality

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