From One Picture to Lost Play: Reviving Ancient Games with Artificial Intelligence for Digital Heritage Conservation

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Abstract

This paper presents a novel technical pipeline for the 3D reconstruction of archaeological artifacts from minimal visual data, specifically single-view image, using Artificial Intelligence-based algorithms. The study addresses a challenging case involving Coptic board games. Due to the inaccessibility of the object caused by different reasons, standard photogrammetric and other survey methods were unfeasible. Leveraging recent advances in computer vision, a deep learning approach derived from the LRM-NeRF family was selected for its superior speed, mesh quality, and generalization performance on out-of-distribution datasets. The reconstruction process included image preprocessing, mesh generation, and geometric optimization using open-source tools. Validation was conducted through metric comparison with similar artifacts held in major museums and expert-in-the-loop reviews. Despite minor texture imperfections due to input limitations, the resulting models proved coherent and analytically reliable. The methodology demonstrates the applicability of 3D reconstruction in low-data heritage scenarios, offering a fully open-source, reproducible and scalable solution for the digital recovery of inaccessible cultural objects. This work not only contributes to the digital preservation of a largely undocumented ludic artifact but also supports the analysis of ancient gameplay dynamics within the broader context of intangible cultural heritage.

1. Introduction: 3D modelling for archaeological artifact study

Three-dimensional modelling has become an indispensable tool in cultural heritage research, enabling scholars to visualize, analyse, and gain deeper insights into historical artifacts and archaeological sites. While digital reconstruction techniques have advanced significantly, challenges remain, particularly in cases where traditional surveying methods fail due to insufficient data. This issue becomes critical when photogrammetry is ineffective due to a lack of high-quality images or, more severely, when acquiring new data is impossible because the object has been lost, destroyed, or remains physically inaccessible.

This challenge is particularly pronounced in archaeology, where artifacts are often discovered in fragmentary conditions, and available documentation is limited. Moreover, logistical and geopolitical factors—such as restricted museum access or ongoing military conflicts—further exacerbate the difficulty of acquiring new data. The absence of comprehensive datasets poses a significant obstacle to researchers and conservators striving to digitally recreate objects with a high degree of accuracy. Additionally, when direct access to artifacts is not feasible, alternative methodologies must be employed to generate reliable three-dimensional reconstructions.

In an era when Artificial Intelligence (AI) is redefining how cultural heritage is preserved, digital data creation and processing emerge as key tools to address the challenges posed by the loss, inaccessibility or fragmentary nature of artifacts. This study fits within that perspective, proposing a data-driven approach to the 3D reconstruction of ancient Coptic games through emerging technologies, with the aim of combining computational methodologies and humanistic knowledge for the protection and enhancement of archaeological heritage.

As part of the European COST Action – Computational Techniques for Tabletop Games Heritage, this study focuses on ancient games for which 3D modelling plays a crucial role not only in digital preservation but also in reconstructing gameplay mechanics and understanding their cultural significance. Unlike textual or iconographic sources, which may provide indirect clues about gameplay, physical remains—such as game boards, pieces, and associated components—are often incomplete or poorly documented. This lack of comprehensive data necessitates the adoption of innovative approaches to digital reconstruction.

Ancient games represent an inherently multidisciplinary field of research, in which historical, archaeological, anthropological and technological approaches converge. Although the ludic and cultural value of play is now increasingly recognized as part of humanity's intangible cultural heritage, much material evidence of these practices has been lost or forgotten. In this context, the present study aims to recover and enhance ancient Coptic games through digital reconstruction, applying AI technologies to fill documentary gaps and contribute to the rediscovery of playful knowledge otherwise destined for oblivion. The purpose of this research is also to lay the groundwork for the analysis of their game dynamics, thereby contributing to a deeper and more culturally aware understanding of past play practice. Starting from this, the aim is to develop sophisticated methods for the preservation of games as a form of ancient and modern cultural heritage and game-centric educational programs.

Ancient Coptic games is a particularly intriguing case study due to their discovery in geographically distant locations, yet exhibiting strikingly similar shapes and dimensions. The study of these artifacts presents significant challenges, particularly because either they are in museums that are not accessible or there are no physical traces except ancient illustrations. This situation has led to delays in research and complications in 3D reconstruction, as standard in-person surveying techniques cannot be applied. To overcome these limitations, the study has focused on leveraging the limited available material, specifically an illustration of the remaining elements of the

game and two photographs per object, one top view and one side view of similar games preserved in museums such as the Louvre, which were used as references for the reconstruction of the case under consideration. This constraint has necessitated the adoption of alternative methodologies, such as single-image 3D reconstruction using algorithm based on AI, to digitally recreate and analyse the games despite the absence of direct access to the physical artifacts.
This paper describes the methodology proposed to address these challenges by promising solutions for reconstructing lost or inaccessible artifacts from limited visual data.

2. State of the art on Artificial Intelligence for generating 3D models

The digital documentation and reconstruction of cultural heritage artifacts have undergone significant evolution, particularly with the advent of photogrammetry and laser scanning techniques. These methods have become standard tools in archaeology, allowing researchers to generate detailed and accurate three-dimensional representations of artifacts and excavation contexts. However, all these methods require either direct access to the physical object or a sufficient number of high-resolution images taken from multiple viewpoints, conditions that are not always met—especially in crisis scenarios or with undocumented collections.
To address these limitations, the field of metric survey has seen growing interest in AI, especially deep learning methods for 3D reconstruction, particularly those that can work with sparse or incomplete visual data. One of the key developments in this area is Neural Radiance Fields (NeRF), introduced by Mildenhall et al. (2020), which allows for photorealistic 3D scene synthesis from a limited number of images. NeRF models learn to represent the volumetric density and color of a scene although they are typically constrained by the requirement for multiple input views and known camera poses. More recently, Gaussian Splatting (Kerbl et al., 2023) has emerged as a technique capable of producing high-fidelity 3D reconstructions with increased efficiency and reduced computational cost. This method represents surfaces using 3D Gaussian distributions, enabling real-time rendering and rapid reconstruction even in scenes with complex geometry. Both the algorithms have been successfully applied in several heritage projects especially implemented in case in which the primary data was of low quality and for expeditious 3D modelling (Basso et al., 2024).
Thanks these AI-based algorithms, new possibilities have opened up in computer vision to obtain 3D reconstructions even from datasets formed from a single image. These algorithms learn, through large datasets of annotated images, to predict the depth of objects and their three-dimensional structure (Hong et al., 2024; Lin et al., 2023; Liu et al., 2023; Long et al., 2023).
The growing release of open-source repositories and pretrained models is accelerating the adoption of these methods across disciplines. This is because the latest research has dealt with generating Gaussian Splats from sparse-view images without the need for known poses (Xu et al., 2025); producing an extremely fast model for 3D monocular reconstruction based on Gaussian Splatting (Szymanowicz et al., 2025); optimizing the trade-off between speed and quality compared to SDS and diffusion-based models (Liang at al., 2025), allowing meshes to be obtained even in cases where insufficient data is available to process images with MVS. In the particular case of 3D reconstructions from 2-4 images (Charatan et al., 2024; Zhang et al., 2024) and from single image previous research integrate, for example, 2D and 3D diffusion models to improve the geometric consistency and visual quality of reconstructions (Basak et al., 2025; Xu et al., 2025).
In previous work, the author (Condorelli et al., 2024) presented an in-depth study of the state of the art of the most recently developed algorithms for single image 3D model generation, classifying them according to the methodology used and tested and benchmarked multiple frameworks, assessing their utility in cultural heritage scenarios.
A significant limitation in evaluating state-of-the-art algorithms lies in the restricted accessibility of training datasets and the unavailability of open-source implementations for several recent models. Consequently, the testing in this work was constrained to those methods with publicly released and replicable code. Preliminary results suggest that many unreleased or under-tested algorithms may not generalize effectively to domain-specific objects, such as those from cultural heritage contexts, due to their training on broad but non-specialized datasets insufficient for capturing the geometric and semantic complexity of such artifacts.
Among the algorithms tested, TripoSR (Tochilkin et al., 2025) was chosen for its rapid and efficient mesh generation, producing detailed reconstructions. TripoSR is a transformer architecture-based 3D reconstruction model designed to rapidly generate 3D meshes from a single image. Developed from the LRM architecture based on NeRF (Hong et al., 2024), it introduces significant improvements in data management, model design, and training techniques. Tests conducted on public datasets show that TripoSR outperforms, both quantitatively and qualitatively, existing open-source alternatives (Tochilkin et al., 2025). The aim in this paper is to test it on a challenging dataset constituted by low quality images and related to asset that are not present in the standard database used for training phase (Deitke et al., 2023). In this sense TripoSR outperforms other algorithms largely due to its superior training data strategy: it leverages a carefully curated, high-quality subset of the Objaverse dataset (Deitke et al., 2023 —augmented with diverse rendering techniques that better mirror real-world image distributions—enhancing its generalization capabilities, especially for domain-specific objects such as those found in cultural heritage.
Considering all these aspects, the selection of the TripoSR algorithm was guided by its high computational efficiency, ability to generate detailed meshes from minimal visual input, and compatibility with limited datasets such as single or dual-view images. Its performance was evaluated in comparison with other state-of-the-art models, and it was found to offer an optimal balance between reconstruction quality and processing speed—factors that were essential given the constraints of this study.
Table 1 shows a comparison between TripoSR with other 3D reconstruction algorithms from single images or limited views just mentioned, based on key criteria such as model quality, speed, and input requirements. TripoSR distinguished itself for its real-time mesh generation that enables rapid prototyping, especially valuable when iterative modeling and comparison are needed. Moreover, it requires minimal hardware resources and no prior calibration, making it highly practical for digital heritage applications with limited infrastructure, demonstrating that at the moment from early tests it was found that TripoSR currently represents a practical solution for the 3D reconstruction of incomplete or inaccessible cultural artifacts, while future research may benefit from comparative benchmarking.
Despite these advancements, limitations remain. Single-image reconstructions may introduce geometric artifacts, and inferred shapes may diverge from real-world proportions without additional constraints or validation.

Algorithm	Input Type	Mesh Quality	Processing Speed	Technical Requirements	Strengths	Limitations
SDS-based models	1–4 images	High (with textual/semantic guidance)	Slow (diffusion-based generation)	Large models, time-consuming inference	Flexible geometry and texture generation	Computationally intensive; variable geometric precision
2D/3D Diffusion	1 image + optional geometry hints	Variable (high with tuning)	Medium-slow	Controlled input conditions needed	Improved geometric consistency for symmetrical objects	Complex pipeline; sensitive to input quality
TripoSR	1 image	Medium-high (structured, clean mesh)	**Very fast (real-time inference)**	Lightweight, direct mesh output	Fast and efficient mesh generation; easy integration	Less photorealistic detail than NeRF or Gaussian Splatting

Table 1. Comparative Table of AI Algorithms for 3D Reconstruction from Limited Images

Nevertheless, when combined with expert input and domain-specific knowledge, these AI-driven reconstructions provide a compelling pathway for preserving and studying artifacts that would otherwise remain digitally undocumented.

3. Proposed methodology: obtaining 3D model from single image dataset

The proposed pipeline for the 3D reconstruction of an archaeological artifact—specifically a historical game board and its associated components—from a single-image dataset leverages state-of-the-art AI-based computer vision techniques and rigorous post-processing validation procedures. The workflow is shown in Figure 1 and structured as the following sequential stages:

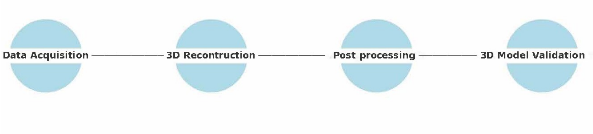


Figure 1. Workflow of the proposed methodology.

- *Data Acquisition and Preprocessing:* the process begins with the acquisition of 2D imagery from diverse sources, including digitized archaeological excavation reports, institutional and museum archives or direct on-site photography where possible. To ensure consistency and optimize performance in later stages, all images undergo standardized preprocessing steps. These include: image normalization (adjustment of exposure, contrast, and white balance); noise reduction; background subtraction; alpha channel verification to ensure transparent backgrounds for use in NeRF-based models.

- *3D Reconstruction:* the core reconstruction stage utilizes the algorithm TripoSR. The model infers geometry and density parameters from a single 2D input using learned priors from large-scale datasets. Where applicable, control is exerted over viewpoint sampling and volumetric density regularization to suppress artifact noise. The generated outputs include final polygonal meshes in standard formats, optimized for topology.

- *Post-processing and Geometric Optimization:* raw mesh outputs often contain imperfections due to occlusion, symmetry assumptions, or lack of surface detail. These issues are addressed via: mesh decimation and remeshing using open source tools like MeshLab, Blender and CloudComapare; surface smoothing and topological repairs, such as hole filling or non-manifold edge correction, in some cases it includes manual refinements. If available, previous survey data cross-referencing could be very useful for geometric validation of scale and feature placement.

- *Validation and Expert-Informed Refinement*: to ensure archaeological validity and cultural accuracy, the reconstructed models are reviewed in a comparative framework. Typological comparison with archaeological records and documented examples of similar artefacts, drawing from museum catalogs and published studies. In this work measurements of a similar artifact were available and were used as the metric reference for validate the reconstruction. Moreover, expert review sessions expert reviews have been requested involving collaboration with archaeologists, game historians, and members of the COST Action “GameTable” network. Any inconsistencies are addressed by refining the models through alternative image inputs or manual adjustments using software such as MeshLab.

4. The Coptic ancient games case study and results

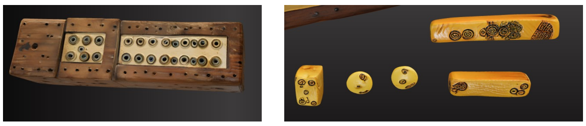
Ancient board games constitute a transnational and trans-temporal cultural phenomenon, often found in contexts far removed, both geographically and chronologically, from the centers where they were invented or most widely practiced. This mobility testifies to the fundamental role that the game played in cultural transmission, interregional contacts, and social and symbolic exchanges between different peoples. Games have been an integral part of human culture for millennia, serving not only as entertainment but also as reflections of social structures, economic systems, and cognitive development. Yet, much of the world’s gaming heritage has been lost due to colonialism, imperialism, and commercialization. What remains are often fragmented artifacts—boards, pieces, and inscriptions—without clear records of the rules or how these games were played.
One of the least explored but fascinating cases in ludic archaeology is that of the so-called Coptic game, a type of ancient board game whose origin and function still remain debated. Archaelogists have identified similar specimens in Egypt and Europe, but the definition and understanding of the game remain incomplete and fragmentary. For this reason, it is interesting to compare all available sources to fully understand the game features and purposes of the object.
Typological comparison with five other known specimens - preserved between the Louvre (Figure 2 and 3), the Egyptian Museum in Cairo (Figure 4), Brussels (Figure 5), and the Swiss Museum of Games - revealed a recurring three-sectional structure:
(1) Base: with two rows of twenty holes for tokens;
(2) Middle section with central and side holes of uncertain function;
(3) Upper section with a central hole (finish line) and decorative holes (Crist et al., 2016).

(a)

(b)

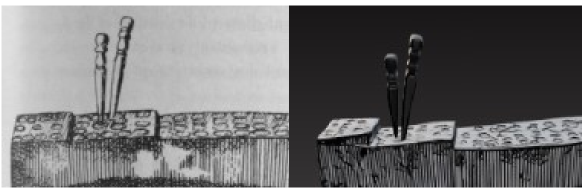
Figure 2. Coptic Game stored in Musée du Louvre, Département des Arts de Byzance et des Chrétientés en Orient: (a) pictures of the original object and single/double view image dataset, (b) 3D model resulted from the proposed methodology implementation

(a)



(b)

Figure 3. Coptic Game discovered in tombe de Thaïas stored in Musée du Louvre, Département des Arts de Byzance et des Chrétientés en Orient: (a) pictures of the original object and single/double view image dataset, (b) 3D model resulted from the proposed methodology implementation.



(a) (b)

Figure 4. Coptic board game (Wolfgang Decker & Allen Guttmann, 1992): (a) pictures of the original object and single/double view image dataset, (b) 3D model resulted from the proposed methodology implementation

These were compared with an ancient illustration of a Coptic-era Senet game table that has holes to hold the game pieces and served as a funerary object (Wolfgang Decker & Allen Guttmann, 1992) (Figure 4).

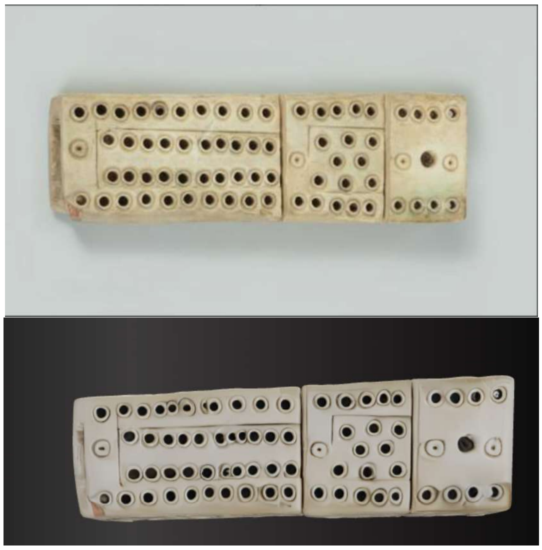


Figure 5. Coptic Game stored in Brussels museum (up) and its 3D reconstruction (down).

The use of advanced single-image reconstruction techniques, supported by AI models such as TripoSR, made it possible to overcome, at least in part, the limitations imposed by the physical absence of the object in the illustration in Figure 4.
By applying the methodology proposed in this study, it was possible to reconstruct in 3D the individual game pieces.
As can be seen from the Figure 2-3-4-5 in which the results are shown, the models obtained are consistent with the source image, although they have small imperfections in texture due to the low quality of the initial image and the presence of decoration details that are not clearly visible. The models were then optimized as far as possible by post-processing algorithms as described in the methodology (Section 3). In order to proceed with the reconstruction of the entire game, the games preserved in the Louvre museum were taken as reference, which as seen from the Figure 2 and 3 they are similar in shape and size and because a frontal, a side and a photo of the pieces are available online. Moreover in the metadata information it is possible to read the measurements that were used to scale the obtained model: Length: 18.1 cm; Width: 4.7 cm; Height: 5.05 cm (with plug); Height: 3.3 cm (top tier); Height: 1.7 cm (last tier). Then implementing the proposed methodology to both of the three available images resulted in the models shown in Figure 2 an 3. Manually, the two models obtained from the two views were combined to have a single 3D model of the object and scaled (Figure 6). Thus, a metric comparison (Figure 7) was performed and the remaining pieces of the case study were overlapped on the whole game preserved in the Louvre.

Figure 6. Merged and scaled model of Coptic Game stored in Musée du Louvre, used as reference.

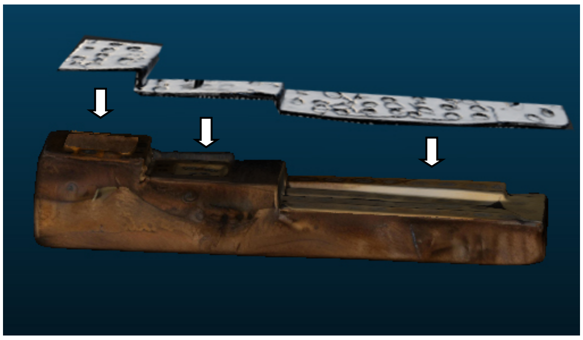


Figure 7. Merged and scaled model of the fragments of Coptic Game from the illustration with the one stored in Musée du Louvre, used as reference.

The results of the reconstruction provide a visual and metric basis on which future comparative analyses and interpretive experiments can be grafted, including in collaboration with other members of COST Action, as reported in next section.

5. Discussion

The results obtained through the 3D reconstruction of the Coptic game boards demonstrate the technological potential of single-image-based methods, particularly when applied to objects of historical and archaeological interest that are no longer accessible. Indeed, the methodology presents easy reproducibility using only open source tools and algorithms that although AI-based do not require large computational resources. In cases where there is no other way to document cultural heritage, the proposed method still allows studies to continue despite difficult situations.
However, the process raises a number of methodological issues that deserve careful consideration. First, the lack of three-dimensional reference data poses a challenge for quantitative validation of the reconstruction. In the absence of a photogrammetric survey or 3D scan of the original find, accuracy assessment was conducted by comparison with known analogous specimens and descriptions found in the literature. This approach, although acceptable in exploratory contexts, needs further formalization to ensure repeatability and transparency in validation criteria. It is also important to recognize the structural limitations of single-image reconstruction, such as the inability to reconstruct unseen portions, or the introduction of geometric and proportional ambiguities, especially in the presence of frontal or heavily occluded images. Such constraints can have concrete repercussions on the archaeological reading of the artifact, for example, by affecting the interpretation of play mechanics, game gestures, or pawn placement.
In spite of these limitations, the proposed digital approach offers a new exploratory channel for ludic archaeology, particularly in cases where the originals are inaccessible or stored in risky contexts or no more existing.
However, the 3D reconstruction obtained through the proposed methodology is not only a technical exercise in digital preservation, but provides a fundamental operational basis for archaeological analysis and interpretation of the rules of the game for these ancient artifacts. With the ability to digitally manipulate three-dimensional models, it is now possible to explore functional hypotheses, propose simulations of use, and evaluate alternative configurations that would be difficult, if not impossible, to examine on the original physical object-often fragmentary or inaccessible.
Currently, scholars affiliated with COST Action, with which the author actively collaborates, are conducting comparative research to infer game rules from reconstructed digital models. The analyses are based on structural and functional similarities with other similar games found in different geographical and chronological contexts. The information that has emerged so far, studied on comparable specimens, includes the number of main holes on the game board that could differ according to local variants of the game; the pegs or pins that served as pawns and the different categories of tokens. The existence of local variations suggested by the presence and irregular arrangement of secondary holes. From this evidence, it is being studied how the pieces were to move, probably along a predetermined track (Crist et al., 2016).
This information, integrated with digital reconstruction, allows for the development of interpretive models that go beyond mere visual representation, enabling archaeologists and game historians to simulate mechanics, test hypotheses, and formulate new theories about the play structure and cultural significance of these artifacts.
The iterative nature of reconstruction-allowing rapid changes and comparisons between versions-has proven particularly useful in the fields of experimental archaeology and game history. In this sense, the combination of AI and archaeological-historical investigation not only fills the gap left by the physical absence of the objects, but also opens new horizons for understanding the intangible cultural heritage related to play in antiquity.

6. Conclusions and future works

The research presented demonstrates how AI-based technologies-particularly 3D reconstruction from single images-can offer innovative solutions to the preservation and study of cultural heritage, especially in contexts where physical objects are inaccessible or compromised. The application of the methodology to the case study of Coptic games highlighted the technical feasibility and scientific utility of the process: the three-dimensional models generated not only preserve the form and proportions of the artifacts, but also serve as analytical tools for interdisciplinary research.
The adoption of advanced single-image 3D reconstruction techniques, based on deep learning models such as TripoSR, demonstrated the feasibility of obtaining a coherent three-dimensional representation even in the absence of the physical object. This approach proved particularly useful in the context of the case study examined, where the original artefacts are inaccessible due to geo-political contingencies.
The application of the proposed methodological pipeline enabled the detailed geometric reconstruction of the individual elements of the game, showing a good adherence to the source image. However, as expected, localised limitations in the rendering of textures were detected, but these were mitigated through the application of automatic post-processing techniques and manual correction.
For the reconstruction of the complete table, an approach based on reconstruction by typological analogy was used, selecting the Coptic Game preserved in the Louvre as a reference. This model was chosen due to the online availability of images and dimensional metadata, used to normalise the metric scales of the 3D model.
In conclusion, the implemented workflow demonstrates that, despite the challenges associated with reconstructing from limited images, it is possible to obtain functional 3D models for morphological and dimensional comparison with other museum specimens. This process constitutes a significant step forward.

The work conducted, in fact, opens new perspectives for the understanding of ancient games and, more generally, for the analysis of intangible heritage related to play culture. Indeed, digital reconstructions allow hypothetical experimentation with game rules, dynamic visualization of possible configurations, and interaction with fragmentary archaeological data in a non-invasive manner.
Future prospects for this research include the development of interactive interfaces for model manipulation by archaeologists and historians; the integration of 3D models into publicly accessible digital museum platforms and virtual exhibitions; the use of Augmented Reality (AR) and Virtual Reality (VR) to recreate immersive experiences that simulate the original gameplay; the construction of comparative databases to trace the evolution of ancient games and cultural connections between different geographic areas.
Finally, the ongoing dialogue between computational technologies and the humanities-as demonstrated by the collaboration with COST Action-presents a promising way to overcome the limitations imposed by material loss and to renew our approach to the study of the past, transforming reconstruction into a critical, participatory and accessible act.
This interdisciplinary approach provides a robust framework for digitally reconstructing and analysing ancient games, offering new insights into their physical structure and gameplay mechanics despite the limitations of available data.

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