Classical Sculpture Analysis via Shape Comparison

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***Abstract*—Modern 3D digital archiving technique provides a reliable assistance to archaeologists. In this paper, we explore a novel framework for digital classical sculpture comparison. Quantitative comparison is introduced, and shape difference is visualized as an indicator to infer unclear points about statue reproduction process in Roman period. Providing a new perspective for the culture relics study, our method plausibly verifies several important assumptions.**

I. Introduction

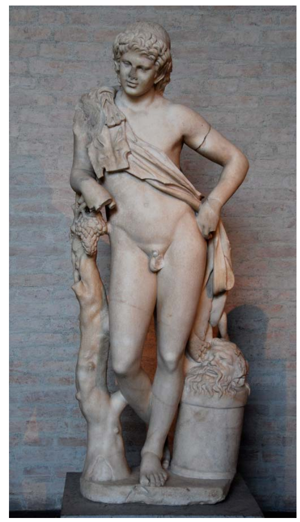
Trying to recover the whole picture of all aspects of social lives based on records and relics, Archaeological research gives us a way to trace the flow of our history. As an important kind of culture relics, classical sculptures never fail to fascinate archaeologists. For instance, the *Resting Satyr* statue created by an ancient Greek sculptor *Praxiteles*, has been found a large number of replicas since the Greek period. [1] Fig. 1(a), 1(b) and 5(b) show three of these copies from the *Glyptothek Museum*, labeled as No.228, 229 and 229A respectively. In the following comparison, we relabel them as Satyr I, II and III for convenience.

Given a certain statue, usually archaeologists would like to figure out the following questions: Who is this statue? Which period does it belong to? Where was it used to be placed? Who is the sculptor and what did he want to express through his work? And so on. To get all these questions solved, subjective analysis is highly relied, meaning that experience, sensitivity and imagination are pivotal in archaeological studies.

A. Motivation

Traditionally, archaeologists analyze differences between classical sculptures by physically comparing either plaster casts or photographs [2]. These approaches suffer from several disadvantages. For instance, there will be information loss if only 2D photographs are used; taking plaster casts is usually a energy-consuming task and may cause physical damages to the original as well. Moreover, traditional method based on subjective judgment is not as convincing as quantitative analysis. Therefore, demand of novel comparison method comes into being.

[1]According to the study in [1], 115 copies have been found in the Mediterranean area, including 15 from Rome, four from North Africa, eight from Greece, two from Spain and one from Gaul, making this sculpture one of the most popular statues in this area.



(a) (b)

Fig. 1. Two marble replicas in *Glyptothek*, Munich. (a): Satyr I; (b) Satyr II. Both these two statues are Roman copies of a Greek original— the *Resting Satyr* by Praxiteles (ca. 320BC).

In this paper, we focus on comparing classical sculptures from the viewpoint of 3D digital archiving. With precise comparison and quantified analysis, we aim to help archaeologists fill the gap between subjective hypothesis and objective evidence in the following aspects:

1) Analyzing Precision of Roman Copies: Archaeologists confirmed that in the 1st century BC, at the end of the Roman Republican period, the production process of sculptural copies was standardized and became increasingly accurate and efficient using a sort of pointing-technique [2], [3]. Due to its mechanical processes this type of copy is called "mechanical copy" but its precision was never visually shown. We would like to visualize precision of the Roman mechanical copy.

2) "Puntelli" Detection: To produce mechanical copies ancient craftsmen developed a technique using reference points, called *puntelli*, to guide the copy process and ensure accuracy [2]. However, usually these reference points were removed or became invisible after finishing the copy, making them difficult to trace. We would like to develop a method that automatically detect these hidden reference points.

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3) Hypothesis Verification: There are several hypotheses about classical sculptures waiting for verification, to which our proposed techniques may contribute. For instance, as for the reproduction process, many archaeologists believe that instead of overall copy, ancient craftsmen copy sculptures part by part, since target statues are usually relatively large. Another example is the attribution inference. For an anonymous work, if certain similarities can be found between it and a statue whose attribution is known, we believe that it is reasonable to infer that their sculptors or at least their workshops are the same [4].

B. Related Work

The way how craftsmen creating statue copies in ancient times are discussed in [2], [3]. They further evaluate shape similarities with 2D manually generated contours and silhouettes. Since most shape information is dropped in the processing, this kind of 2D comparison is not accurate enough. Besides, it is difficult to illustrate subtle differences.

In the recent studies about cultural heritage preservation and analysis, 3D digital replicas play an increasingly important role [5]. With the help of 3D scanning techniques, accurate digital copies of real-world objects are widely used in various archaeological studies. A representative work about digital archiving of cultural heritage is presented in [6]. Notice that the entire building of the *Bayon* temple at *Angkor* was digitally recorded in this *Bayon Digital Archival Project*. With the obtained digital copies, further analysis can be explored, such as to restore and classify those famous *Bayon* facial sculptures [7], [8]. Besides, with the help of digital archiving technique, a repetitive use of model parts for different bronze statues in a sculptors workshop has been attested in [4].

Shape analysis and comparison is an active field in computer science as well. A typical approach to analyze a set of shapes is statistical shape analysis, which is discussed in [9]. Statistics are measured to describe geometrical properties of similar shapes and usually principal component analysis (PCA) [10] is used to analyze the shape variability. Besides, partial shape matching methods, such as [11], [12], also play an important role in shape comparison task.

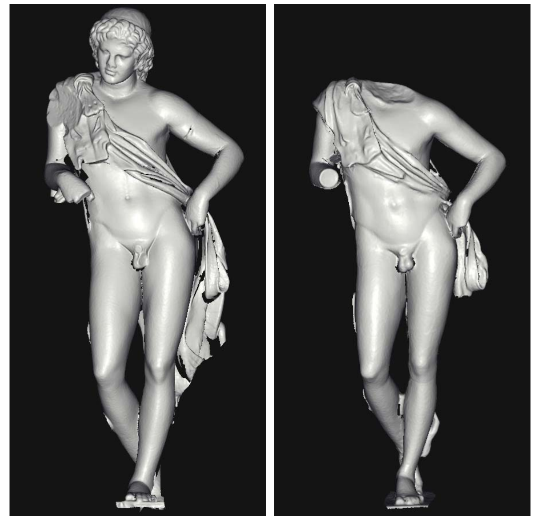
C. Contributions

We explore a complete framework for numerically comparing 3D sculptures. Given two copies of a same original, we first rigidly align them together, and then visualize the shape differences between corresponding points. Compared with previous methods where only 2D silhouettes manually obtained are used, our analysis contains richer information and is more accurate as well. With the visualized dissimilarities between statues given by our method, it is much easier for archaeologists to compare similar sculptures for further analysis. Furthermore, several important archaeological hypotheses are verified by our proposed method.

II. The Shape Comparison Framework

A. Preprocessing

Generally speaking, in order to obtain a complete 3D digital copy, scans from different viewpoints are necessary.



(a) (b)

Fig. 2. Digital copies of the two Satyr sculptures shown in Fig. 1. (a): Satyr I; (b) Satyr II.

Since these pieces of raw data cannot be directly used for our further analysis, a preprocessing, including data cleaning, registration and merging, has to be carried out first. Detailed description about this preprocessing can be found in [13], [14]. Fig. 2 shows two digitized *Satyr* statues after preprocessing, which correspond to the same sculptures shown in Fig. 1.

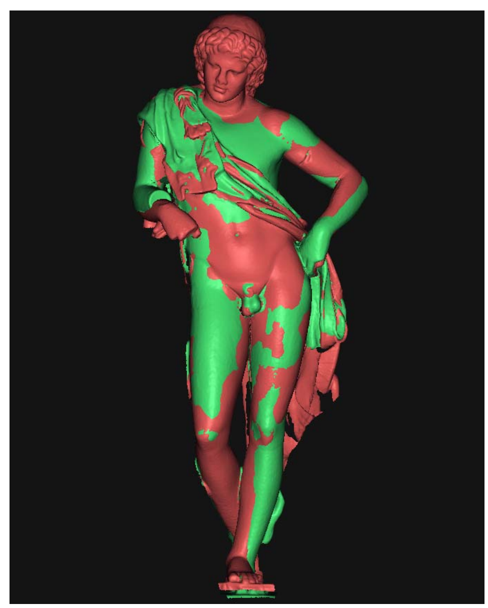


Fig. 3. A demonstration of rigid alignments— Satyr I in red and Satyr II in green.

B. Rigid Alignment

After entire digital copies have been obtained, we align these 3D models for further comparison. Here the term "alignment" means that we would like to automatically adjust

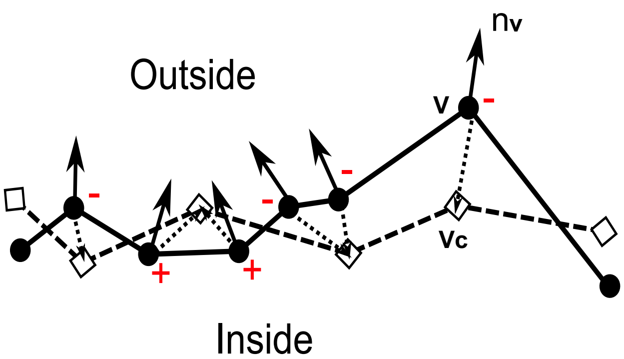


Fig. 4. An illustration of calculating the distance between two shapes, which are denoted with dotted and solid lines respectively.

the position and posture of one object, including rotation, translation and scaling, making it match to the other as much as possible. Notice that since target objects are supposed to be very similar to each other, just rigid alignment methods would be adequate.

The *Iterative closest point* (ICP) algorithm, first introduced in [15], is the current baseline method for rigid shape registration. It is used to align two objects by minimizing the average distance between them. Several variants of ICP have been proposed. In this paper, an extended version of ICP with acceleration, presented in [13], is utilized. We apply this algorithm on two under-comparing statues in order to get the optimist transformation that best aligns these two objects. Fig. 3 shows a demonstration of this rigid alignment process.

C. Visualization of Shape Differences

Based on the alignment results, we adopt a correspondences matching scheme based on nearest neighbor searching. Our matching strategy is simple: for each point on one statue, we search the closest point on the other one, and assign it as the corresponding point. Then distances between these corresponding point pairs can be used to evaluate the shape difference.

In detail, given corresponding point pairs $\mathbf{v}$ and $\mathbf{v}_c$ obtaining from base and target objects respectively, as well as the normal vector $\mathbf{n}_\mathbf{v}$ at $\mathbf{v}$, the signed shape difference can be defined as:

$$d \doteq \begin{cases} sgn(\mathbf{n}_\mathbf{v} \cdot (\mathbf{v}_c - \mathbf{v})) \cdot \|(\mathbf{v}_c - \mathbf{v})\| & \text{if } \mathbf{v}_c \neq \mathbf{v}, \\ 0 & \text{otherwise,} \end{cases} \quad (1)$$

where $sgn(\cdot)$ is the sign function. Fig. 4 illustrates this calculation.

In order to make comparison result more intuitive and easier to understand, we visualize these signed shape differences similar as [16]. Points are stained according to their corresponding signed shape differences. An example is illustrated in Fig. 5(f).

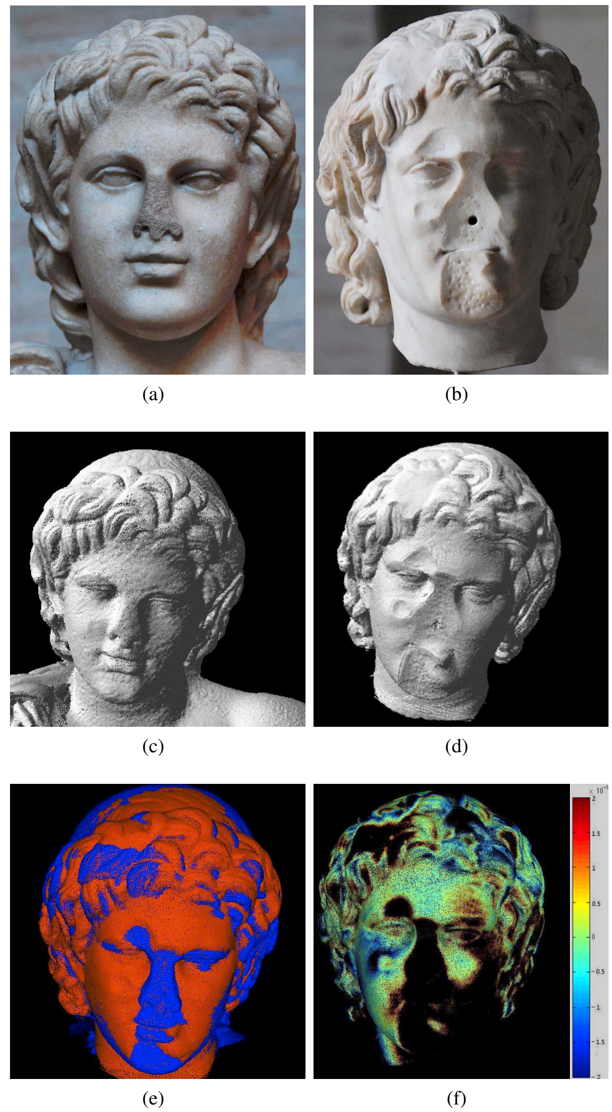


Fig. 5. An example of classical sculpture comparison. As shown in (a) and (b) respectively, the head part of two marble statues, *Satyr I* and *Satyr III*, are utilized as target objects. (c) and (d) are the corresponding digital copies. (e) shows the rigid alignment result and (f) visualizes the shape difference. Based on the result shown in (f), we find that the undamaged facial part of *Satyr III* coincides the corresponding part on *Satyr I* quite well.

III. CASE STUDIES

For verification test, we used digital copies of plaster casts from the *Museum for Casts of Classical Sculpture* in Munich, Germany. Their corresponding originals are marble replicas of masterpieces created in Classical period. All digital copies were acquired by *Konica Minolta* "*Vivid* 9i" 3D laser scanner, with a very high measurement accuracy of $\pm 50\mu$m.

A. Analyzing Precision of Roman Copies

We first compare the Satyr statures. Fig. 5 demonstrates the shape difference between the heads of *Satyr I* and *Satyr III*. Points are stained according to their corresponding signed

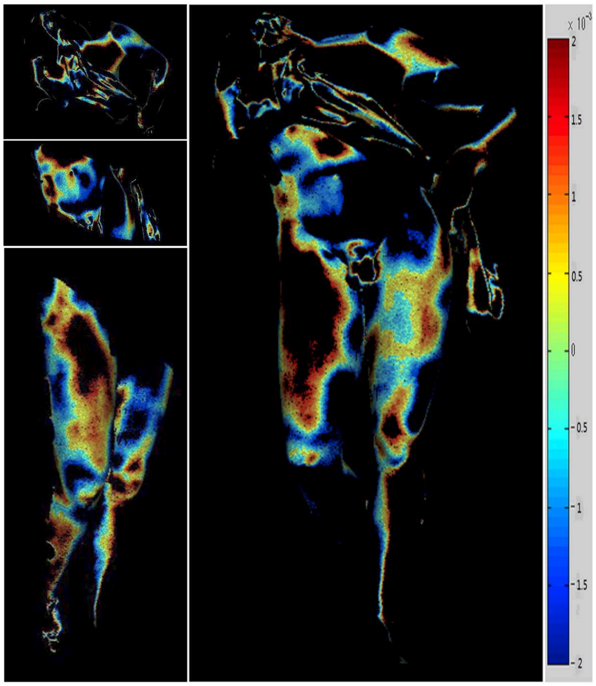


Fig. 6. Shape dissimilarities based on locally and overall alignment. the three relatively smaller blocks are matching results based only on the part of chest, belly and legs respectively, while the largest block shows the result using overall registration.

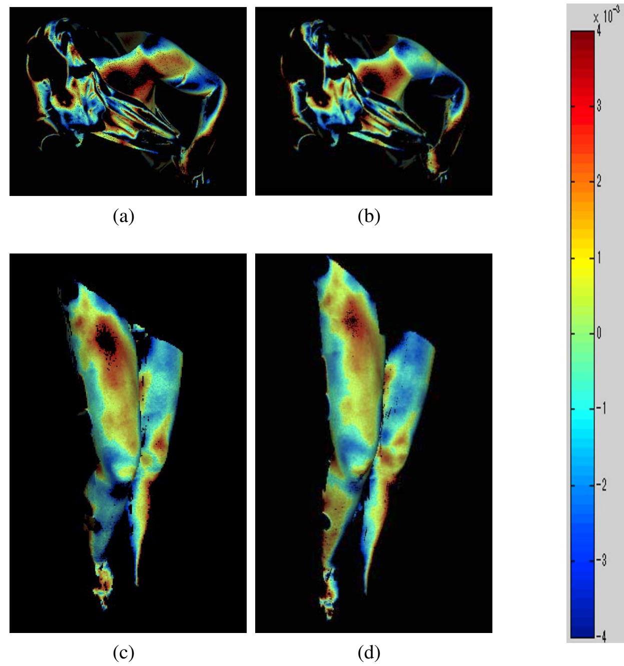


Fig. 7. Visualization of dissimilarities between *Satyr I* and *Satyr II*. Two different strategies are used during the comparison: (a) and (c) show the shape differences based on overall alignment, while (b) and (d) are better matching results where the front part are of higher priority during alignment. This supports the assumption that the front part of statues got more attention during the copy process in Roman period.

distances— red and blue correspond to regions of convex and concave differences respectively, and green means the shape difference is almost zero, meaning a near-perfect match in that region.

Comparing Fig. 5(f) and Fig. 6, we observed that the head part got paid much more attention to than the body part during the ancient reproduction process, since the errors of head part look much smaller than that of the body part.

B. The Phased Replication Hypothesis

In order to check whether ancient craftsmen copied statues part by part, we prepared results where only a certain part, e.g., chest, belly or legs, are left for comparison, as well as the result with overall alignment. Fig. 6 shows the comparison. We can observe that separately aligned result achieves more accurate matching than the overall registered one. Besides, as shown in Fig. 7, compared with the overall matching, shape differences become smaller if only the front part is used for alignment. These phenomenons support the hypothesis that front part are given more attention during the reproduction and the copy process was very likely to be carried out part by part.

C. "Puntelli" Detection

Due to their highly archaeological reputation, we chose the two statues of *Satyr* shown in Fig. 1 as the experimental objects for the reference points detection.

As we explained in the introduction part, "puntelli" is a kind of reference points made by craftsmen to ensure the accuracy during statue replication. Therefore, when comparing two copies originated from the same source, the shape dissimilarity between them should reach its minimum at these reference points. Then we can reasonably locate these "puntelli" via rigid shape comparison. For instance, in the comparison shown in Fig. 7, we may infer those dyed-green salient points, such as those convex points on lower abdomen and knees, are very likely to be "puntelli".

D. Attribution Inference

The statue of *Amazon Sciarra* shown in Fig. 8a is a Roman marble copy from a Classical bronze original. The sculptor's name of the original, Kresilas or Polykleitos, is still in controversy and till now there is no conclusive evidence that can support any one of these hypotheses.

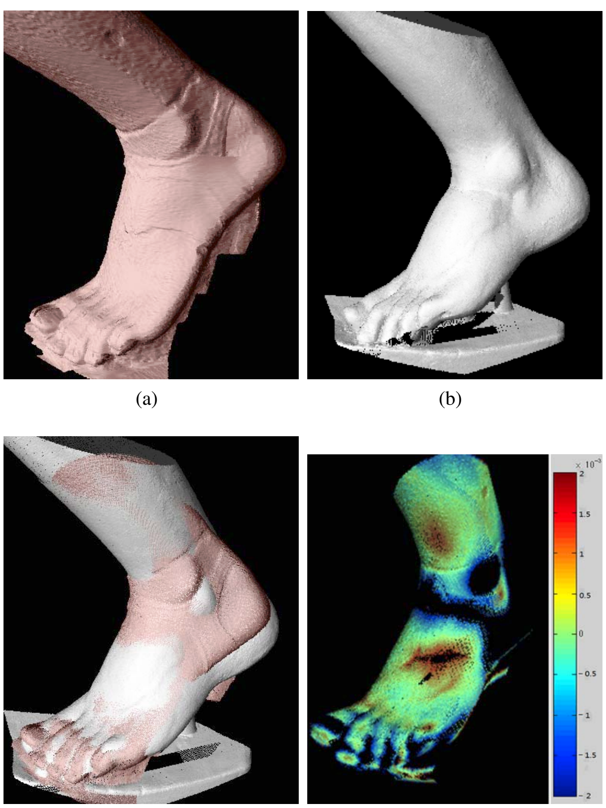
Here we decided to employ the same method as [4] for this study. The *Diadoumenos in Athens* statue by Polykleitos, shown in Fig. 8b, is chosen to compared with. We compared the two left feet of *Diadoumenos* and *Amazon Sciarra*. Fig. 9 shows the comparison result. Notice that a relatively large area of the foot is dyed green, meaning the shape dissimilarities are very close to zero. This support the speculation that this Amazon statue is more likely created by Polykleitos, not Kresilas.

IV. Summary

Modern digital archiving technique provides a novel and reliable assistance to modern archeology researches. As one

(a) (b)

Fig. 8. Two statues for attribution inference: (a) *Amazon Sciarra* in Copenhagen; (b) *Diadumenos* in Athens. (a) is also called "*Kresilas' Amazon*", because most archaeologists believe it is to be attributed to Kresilas.



(a) (b) (c) (d)

Fig. 9. Comparison of the two left feet from two different statues— "Amazon Sciarra" and "Diadoumenos in Athens". (a) and (b) show the two target shape; (c): result after rigid alignment; (d): visualization of the shape difference.

of those representative problems, quantitative analysis based on 3D shape analysis help archaeologist to easily find subtle but vital information hidden behind shapes. The application of 3D shape analysis is just unfolding in the interdisciplinary with culture research.

In this paper, we proposed an intuitive 3D shape comparison procedure and apply it on the sculpture data from Glyptothek, Munich. We showed the shape analysis of classical sculptures using their 3D shape data to detect the local shape difference as an indicator to determine the copy standard of sculpture reproduction in Roman period and infer attribution of masterpiece. The proposed method successfully verifies archaeological assumptions and provides a new perspective to heritage protection and research.

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