Analysis of Classical Sculpture with Shape Comparison (形状比較を用いた古典彫刻分析)

by

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A dissertation submitted in partial fulfillment of the requirements for the degree of

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February 2014

Abstract

Modern three dimensional digital archiving technique provides a reliable assistance to archaeologists. Although a number of culture heritages and relics have been preserved by digital modelling so far, how to further utilize those three dimensional data and mine the deep information is still under exploration.

In this thesis, an approach of classical sculpture analysis via three dimensional model comparison is discussed. In order to fill in the current gap between subjective reasoning and rarely accessible cultural relics, we explore a complete framework for digital classical sculpture comparison. This framework consists of mainly three steps: model construction, alignment of two models and difference evaluation. Having three dimensional models in hand, a Region of Interest Guided Alignment is introduced so that it becomes possible to emphasize specific regions on model. Euclidean distances of correspondent point pairs between two models are calculated as indicator of shape difference and moreover, those are colour-coded to present the intuitive difference distribution. In addition, quantitative evaluation of those point to point distance is introduced to achieve numerical similarity assessment.

Experimental results using real three dimensional scanning data of several statues shows the effectiveness of our method. Inferences based on our comparison results appear to be consistent with historical materials, which assures us that our method is reliable as a base of sculpture analysis.

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TO MY FAMILY AND ALF

Acknowledgments

First of all, I would like to express my deepest gratitude to professor Katsushi Ikeuchi, who kindly supervised me during my master student time. It is him who gave me a wonderful opportunity to come to the University of Tokyo, introduced me to the current research field, taught me how a researcher should be, and helped me to conquer the difficulties ahead. He is the advisor not only in academics but in life as well. I feel a great previlidges as his student.

I am appreciate to professor Kyoko Sengoku-Haga, who supervised me in this sculpture comparison research. During this project, she patiently introduced the related backgound knowledge to me, the totally layman to archaeology and helped me with analysing the experiment result. The fruitful discussion with her always inspires me with new idea. Her rigorous academic attitude is the best example I should learn from.

I want to acknowledge the fabulous CVL staffs. Thank to Dr. Bo Zheng, my direct senior associate, who provided me with encouragement and support in various ways. He lead me into this research and gave me significant advices. Thank to Prof. Takeshi Oishi, Prof. Shintaro Ono, Dr. Takeshi Masuda, they all contributed in this project and provided significant comments and suggestions in our weekly meeting. My acknowledge also goes to the considerate sacristies of CVL. Thank you very much for helping me with complex documents in Japanese.

I would also like to thank my companions in CVL. I also want to thank you for letting my master student time be an enjoyable memory, and for your brilliant comments and suggestions, thanks to you.

Special thank to Panasonic Scholarship, who supported me financially during my days in Todai and cared about me in life and career plan. Thanks to all the people who helped me in Japan.

At the end I would like to show my thanks to my family. Words cannot express how grateful I am to my mother and my father. Your love to me was what sustained me thus far. I would like express appreciation to Alf who serves as a great senior and partner not only in research but in life as well.

No two leaves could ever be exactly the same.

Gottfried Wilhelm Leibniz

1 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.

Besides of the aesthetic impression, the comparison serves as the basic stage of the whole sculpture analysis Among varieties of ways of research. Information such as sculpture fineness or similarity appear directly by contrast and moreover, such information give us hint to unveil more. The ancient sculpture construction process, the attribution of a masterpiece... Mysteries underneath sculptures are waiting for us to solve and fortunately, they can be explored by shape comparison.

1.1 Similar Sculptures Comparison

Narrowing down the topic of sculpture comparison, we would like to focus on statues which look similar to each other. Similar statues include from different copies of one statuary type, to different statues with same pose or even different characters just sharing alike parts(such as foot or hand). Thus our comparison enjoys the benefits to be limited to concrete sense rather than abstract description such as symbolic meaning or emotion expression, so that make digitalization feasible. Fig. 1.1.1 shows an instance of similar sculptures.

(a) **(b)**

Figure 1.1.1: 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).

But difficulty still exists. Appreciation of sculpture depends upon the ability to respond to form in three dimensions. That is perhaps why sculpture has been described as the most difficult of all arts; certainly it is more difficult than the arts which involve appreciation of flat forms, shape in only two dimensions [1].

Just as Henry Moore said, "A sculpture has requirements more than two-dimensional shapes and also relates to distances judgement or depths perception. People develop the ability to judge roughly three-dimensional distances mainly for personal safety and practical needs, unfortunately however, though they may attain considerable accuracy in the perception of flat form, they do not make the further intellectual and emotional effort needed to comprehend form in its full spatial existence. On the other hand, a sensitive observer of sculpture must also learn to feel shape simply as shape, not as description or reminiscence. He must, for example, perceive an egg as a simple single solid shape, quite apart from its significance as food,or from the literary idea that it will become a bird."

Such high accuracy requirement gives modern computer vision technique a chance to play its strength. Perhaps it is a good idea to trace what a sculptor must did thousands years ago just by analysis the shape of his works. Under the shape displacing in the air for centuries, we hope to disinterred a past era where ancient sculptures strive continually to think of, and use, form in its full spatial completeness and emotion expressions. Let the what sculptor most cares, the shape, tell story itself.

1.2 Motivation and Goals

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

[1] Henry Moore *The Sculptor Speaks* from *The Listener*

experience, sensitivity and imagination are pivotal in archaeological studies.

In this thesis, we focus on comparing classical sculptures from the viewpoint of 3D digital archiving. Specially, the comparison between alike copies of one statuary type and similar statues arouse our interests. With highly accurate three dimensional model of sculptures, previously impossible processing such as arbitrary cut and view form inside can be achieved now. Moreover, comparison of three dimensional models shows us result by exact number. It is a method independent on human sensation so that human error is avoided. With precise comparison and quantified analysis, we aim to help archaeologists fill the gap between subjective hypothesis and objective evidence.

1.3 Related Works

1.3.1 Traditional Sculpture Comparison

Traditionally, archaeologists analyse differences between classical sculptures mainly by comparing plaster casts or photographs.

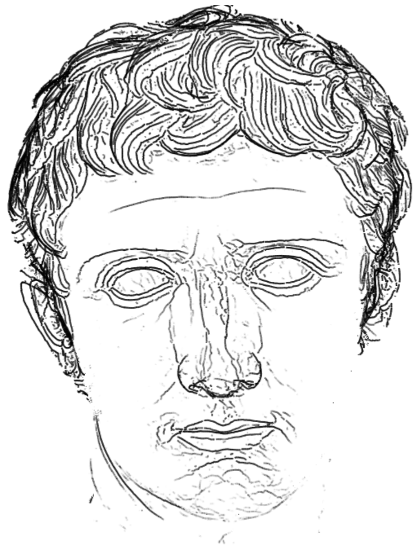
In representative works [1], the way how craftsmen creating statue copies in ancient times are discussed and the authors further evaluate shape similarities with 2D manually generated contours and silhouettes. Fig. 1.3.1.

However, 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 a word, 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 judgement is not as convincing as quantitative analysis. Therefore, demand of novel comparison method comes into being.

(a)

(b)



(c)

Figure 1.3.1: An example of traditional sculpture comparison methods. (a) this figure is the explanation of how the Roman copies were made using comparison by profile line[1]. (b) and (c) shows an example of feature contour extraction. (b): the target model; (c): ridges and valleys on the target model[2]

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1.3.2 Digital Heritage Archive

In the recent studies about cultural heritage preservation and analysis, 3D digital replicas play an increasingly important role [3]. With the help of 3D scanning techniques, accurate digital copies of real-world objects are widely used in various archaeological studies.

A famous work about digital archiving of cultural heritage such as Digital Michelangelo Project [4] preserved the 3D model of famous sculptures and initiates in the research of digital archive. Bayon Digital Archival Project, another representative work about modelling cultural heritage is presented in [5, 6]. Notice that the entire building of the *Bayon* temple at *Angkor Thom* was digitally recorded, moreover, novel scan mechanisms were in utilization[7], new sensors were developed, such as Climbing Sensor[8] and Flying Laser Range Sensor[9], and new modelling techniques were proposed including fast alignment and parallel merging[10].

With the obtained digital copies, further analysis can be explored, such as to restore and classify those famous *Bayon* facial sculptures [11, 12]. Besides, with the help of digital archiving technique, a repetitive use of model parts for different bronze statues in a sculptor's workshop has been attested in [13]. Moreover, a trial of sculpture categorization via local shape comparison[14] has been proposed in 2013.

1.3.3 Shape Comparison in Computer Vision

Shape analysis and comparison is an active field in computer science as well. A typical approach to analyse a set of shapes is statistical shape analysis, which is discussed in [15]. Statistics are measured to describe geometrical properties of similar shapes and usually *Principal Component Analysis* (PCA) [16] is used to analyse the shape variability. Besides, partial shape matching methods, such as [17, 18], also play an important role in shape comparison task.

Serves as a basic step of shape comparison, how to get correct and meaningful shape correspondence is also a important topic in this issue. A survey done by Kaick, et. ac in [19] reviews the progression of the research on shape correspondence. Correspondence problem could be divided to some branches: dense vs. sparse, partial vs. full, nonrigid vs. rigid. Each of them has its own challenges and usually has relation to another. For instance, rigid registration with full matching is discussed in [20–22] while in [23–25], authors focus on sparse correspondence with more general case. Non-rigid matching problem is another huge category and more general. Non-rigid but isometric correspondence[26–28] and further constraint-less cases such as in [29] and [30] are explored respectively. The trend that shape correspondence develops from low-level pure geometry analysis to the higher-level problem of semantic reasoning, and has promoted the research of shape comparison accordingly.

Inspired by those prior works, we would like to step forward beyond digital archive, to quarry the messages left by our ancestor sculptors. Specifically, we focus on the comparison of classical sculptures by three dimensional modelling and analysis method.

1.4 Pipeline of Sculpture Analysis with Shape Comparison

Basically speaking, the pipeline of our sculpture analysis with shape comparison includes two parts. One is the relatively low level geometric analysis part: 3D Models Pair-wise Alignment & Spacial Distance visualization; the other one is the high level Reasoning & Hypothesis based on the shape comparison results. These two parts sometimes iteratively work in our pipeline.

1.4.1 Pair-wise alignment & difference visualization

This part is based on the precondition 3D models are already available. In alignment, two models are set in one coordinates and overlaid together as much as possible under a certain criterion. In our case, a rigid alignment method with nearest neighbour rule is utilized to align two similar sculpture. Furthermore, a *Region of Interest Guided Alignment* is introduced so that it becomes possible to emphasize the key part. Distances of point pairs between two models are calculated as indicator of shape difference and moreover, those are colour-coded to present the intuitive difference distribution. In addition, statistical evaluation of those point to point distance is introduced to achieve numerical similarity assessment.

1.4.2 Reasoning & hypothesis

Based on the numerical comparison result, processing such as calculating statistic index can be implemented. Combined with historical material in archaeology, further reasoning is deduced, hypothesis is proposed and new finding is discovered.

1.5 Contributions

We explore a complete framework for numerically comparing 3D sculptures. Given two copies of a same original, we first rigidly align them together with the consideration of local emphasis, 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, experimental results using real three dimensional scanning data of several statues shows the effectiveness of our method. Inferences based on our comparison results appear to be consistent with historical materials, which assures us that our method is reliable as a base of sculpture analysis.

1.6 Thesis Overview

Chapter 2 explains the whole framework of shape comparison. This framework consists of 3 parts: preprocessing and model construction, ROI-guided alignment and numerical expression of sculpture difference. It demonstrates how the preference of emphasizing area approaches and the user friendly result expression.

Chapter 3 shows the application of sculpture comparison in hypothesis verification based on precise comparison analysis. 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.

In Chapter 4 we take one step forward to proposed inferences and claim our assertions based on comparison result. The contents are composed of discussion of Polykleitos's models, the copy reliability ranking problem of several "Doryphoros", the "canon" of ancient sculptures and the trial of "ideal" standard copy construction.

Chapter 5 concludes the whole thesis. We review the main contribution and summarize applications as well as limitations. Possible extensions and future work are also discussed in this chapter.

2

The Shape Comparison Framework

In this chapter, we will introduce the framework for digital classical sculpture comparison and explain how it works. This framework consists of mainly three steps: model construction, alignment of two models and difference evaluation.

2.1 Preprocessing and model construction

2.1.1 Preprocessing

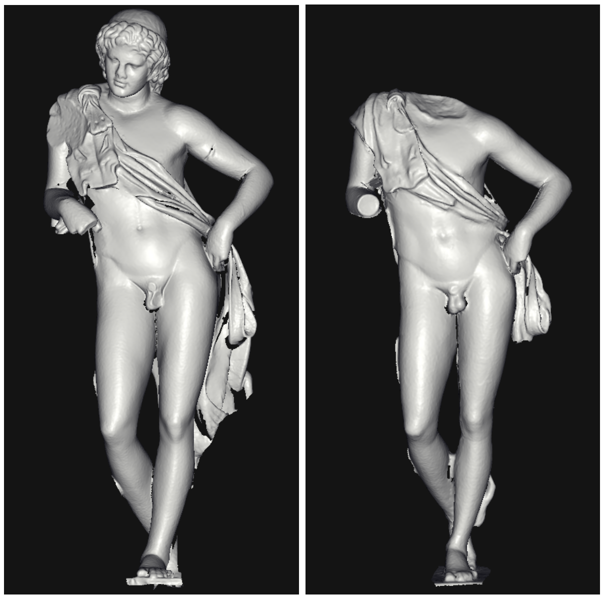
Generally speaking, in order to obtain a complete 3D digital copy, scans from different viewpoints are necessary. Since these pieces of raw data cannot be directly used for our further analysis, a preprocessing, including data cleaning, hole filling, registration and merging, has to be carried out first. Detailed description about this preprocessing can be found in [31, 32].

2.1.2 Merging and Model Construction

Notice that for the merging processing, the method proposed in [32] is utilized. Briefly speaking, modelling object shapes from multiple range images requires three processes: correction of measurement errors, registration of data shapes, and integrating them as a unified shape representation. The utilized merging method solves these tasks simultaneously. Discrete samples of the *signed distance field* (SDF) of the object surface are used as the shape representation. If the data shapes are registered correctly, the SDFs should match in the common coordinate system. The data shapes are first integrated by averaging the data SDFs assuming that they are roughly preregistered. Then, each data shape is registered to the integrated shape by estimating the optimal transformation. Integration and registration are alternately iterated until the input shapes are properly registered to the integrated shape. Weighting values are controlled to reject outliers derived from measurement errors and wrong correspondences. The proposed method does not suffer from cumulative registration errors because all data shapes are registered to the integrated shape. From the SDF shape representation, a polygon surface model is directly generated. The method was tested on synthetic and real range images.

The limitation of the utilized merging method is that it needs to assume the data shapes are roughly preregistered in advance, which can be given by correspondence established manually or automatically by using existing techniques such as invariant features, graph matching, geometric hashing, or combinational optimization.

Fig. 2.1.1 shows two digitized *Satyr* statues after preprocessing, which correspond to the same sculptures shown in Fig. 1.1.1.



(a) (b)

Figure 2.1.1: Digital copies of the two Satyr sculptures shown in Fig. 1.1.1. (a): Satyr I; (b) Satyr II.

2.2 An ROI-guided 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 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.

2.2.1 Classical Rigid Alignment

The *Iterative closest point* (ICP) algorithm, first introduced in [33], is the current baseline method for rigid shape registration. It is used to align two objects by minimizing the average distance between their point clouds.

ICP is often used to reconstruct 2D or 3D surfaces of the same object from different scans which sharing overlap parts. It can be applied to localize robots and achieve optimal path planning, to co-register bone models, and so on. The algorithm is conceptually simple and is commonly used in real-time. It iteratively revises the transformation (translation, rotation) needed to minimize the distance between the points of two raw scans. Briefly speaking, the transformation estimating procedure is as follows.

Inputs: Make initial estimation of the transformation between two clouds of points. Set the threshold for stopping the iteration.

Output: refined optimal transformation.

Regard the "nearest neighbour" point as corresponding point, set up correspondence.

Essential steps are:

1) Estimate transformation parameters using a mean square cost function.

2) Transform the points using the estimated parameters.

3) Iteration (re-associate the points and so on).

In the "classic" variant of the ICP algorithm for rigid alignment, given two point sets as P and Q, an assignment is established between every point $p \in P$ and its closest point in Q, according to a given distance metric. In this meaning, ICP becomes a full correspondence method. An illustration of ICP is shown in Fig. 2.2.1.

Several variants of ICP have been proposed. In Zhang's work in 1994[35], a modified K-D tree algorithm is proposed for efficient closest point computation, and a statistical method based on the distance distribution is used to deal with outliers, occlusion, appearance and disappearance, which enables subset-subset matching.

What should be paid attention to is that the initial positions of the point sets tremendously influence the final result of the ICP algorithm, because the first correspondence is derived from this initial estimation. Thus, a crucial step in ICP-based methods is to perform a pre-alignment of the shapes so that the algorithm keeps off

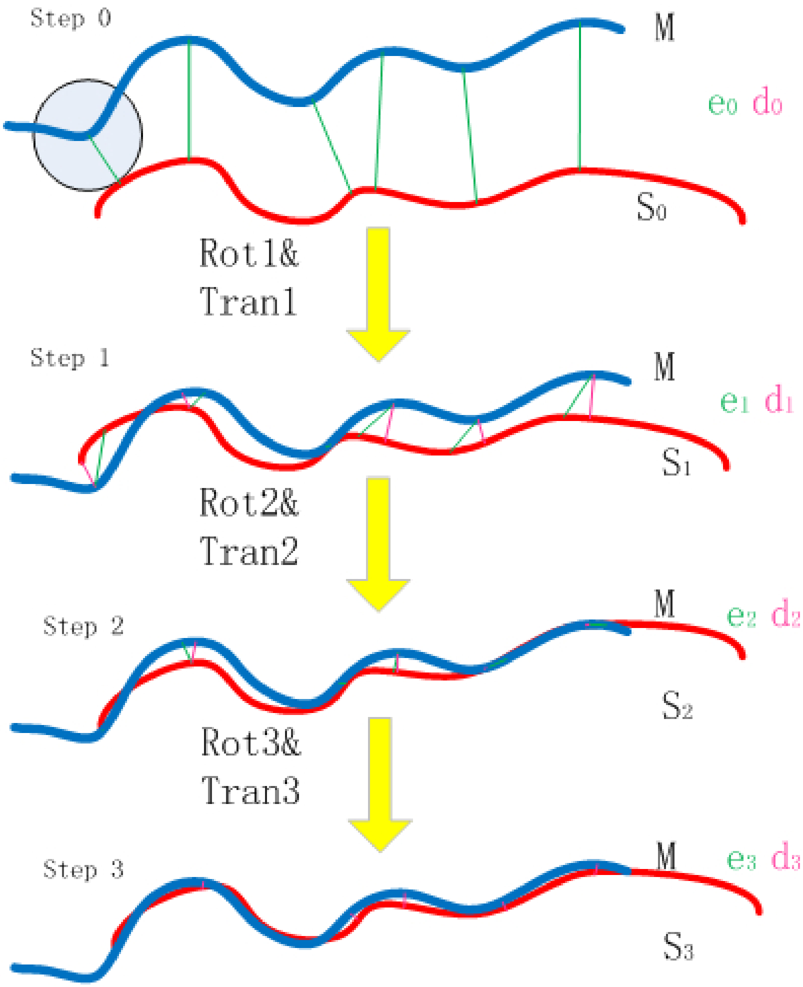


Figure 2.2.1: This figure shows a typical iteration process of ICP, which is originally presented in [34]. Initially, the closest points are found and connected by green lines. Then in step 1, the scene set is update by *Rot1* and *Trans1*, and the correspondences change. The new closest points are connected by pink lines, not the previous green lines. From step 0 to step 3, the scene set keeps move closer to the model set. This process will repeat until convergence, which means the two point sets are aligned well.

getting trapped in local minima. This issue is addressed by different forms of pre-alignment. The classic solution is to automatically pre-align the shapes with *Principal Component Analysis* (PCA)[22]. Recently, another effective solution has been also proposed which is pre-alignment based on the reflection symmetry axes of the shapes[36].

2.2.2 A ROI-guided Alignment

In this paper, a fast alignment using index images, an extended version of ICP, presented in [37], is included. It is a fast, simultaneous alignment method for multiple range images.

Generally speaking, the most time-consuming task in aligning range images is searching corresponding points. The fastest searching method is the *Inverse Calibration* method. However, this method requires pre-computed lookup tables and precise sensor parameters. In [6], a fast searching method is proposed using index images, As shown in Fig. 2.2.2. It works as look-up tables and are rapidly created without any sensor parameters by using graphics hardware.

This algorithm employs points and planes to evaluate relative distance. The corresponding pairs are searched along the line of sight. Here, the line of sight is defined as the optical axis of a range sensor. Denote one mesh as the base mesh and its corresponding mesh as the target mesh. An extension of the line of sight, from a vertex of the base mesh, crosses a triangle patch of the target mesh and creates the intersecting point. In order to eliminate false correspondences, if the distance between the vertex and the corresponding point is larger than a certain threshold value, the correspondence is removed. This correspondence search is computed for all pairs of mesh models.

Though the threshold distance is given empirically as l_{given}, it is compared with the average distance of all corresponding points $\hat{r}$, and the smaller value is selected as l_{th},

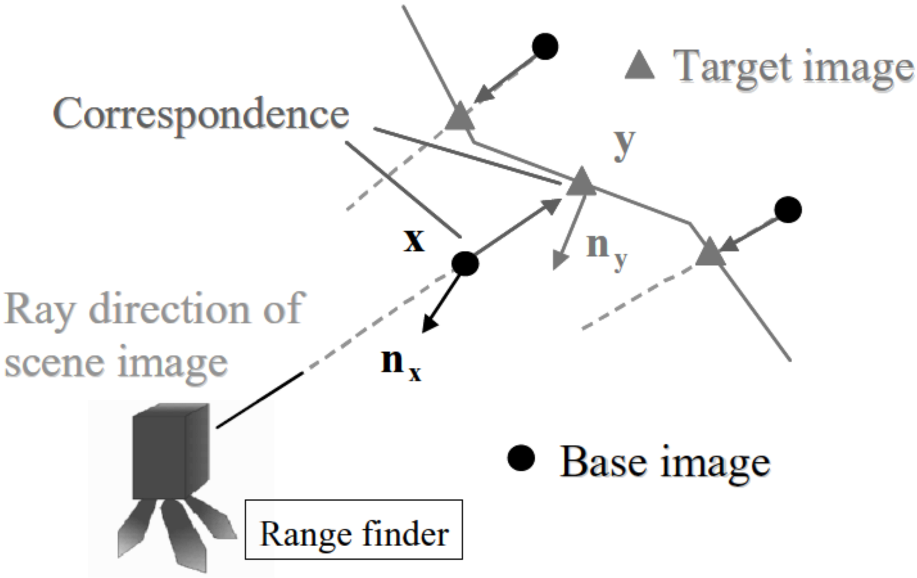


Figure 2.2.2: Searching for corresponding points along the line of sight. This figure is originally presented in [6], and reproduced here with permission.

which is defined as below:

$$l_{th} = \begin{cases} l_{given} & \text{if } l_{given} < \hat{r}, \\ \hat{r} & \text{otherwise.} \end{cases} \tag{2.1}$$

Here $\hat{r}$ is defined as:

$$\hat{r} = \frac{1}{N} \sum_{i}^{N} \|\mathbf{y}_i - \mathbf{x}_i\|, \tag{2.2}$$

where N is the number of vertices included in the base mesh.

We apply this algorithm on two under-comparing statues in order to get the optimist transformation that best aligns these two objects. Fig. 2.2.3 shows a demonstration of this rigid alignment process.

Specifically, consider that in our sculpture comparison case, the situation of sculpture damage or parts missing happens, it hardly satisfies one to one correspondence. For

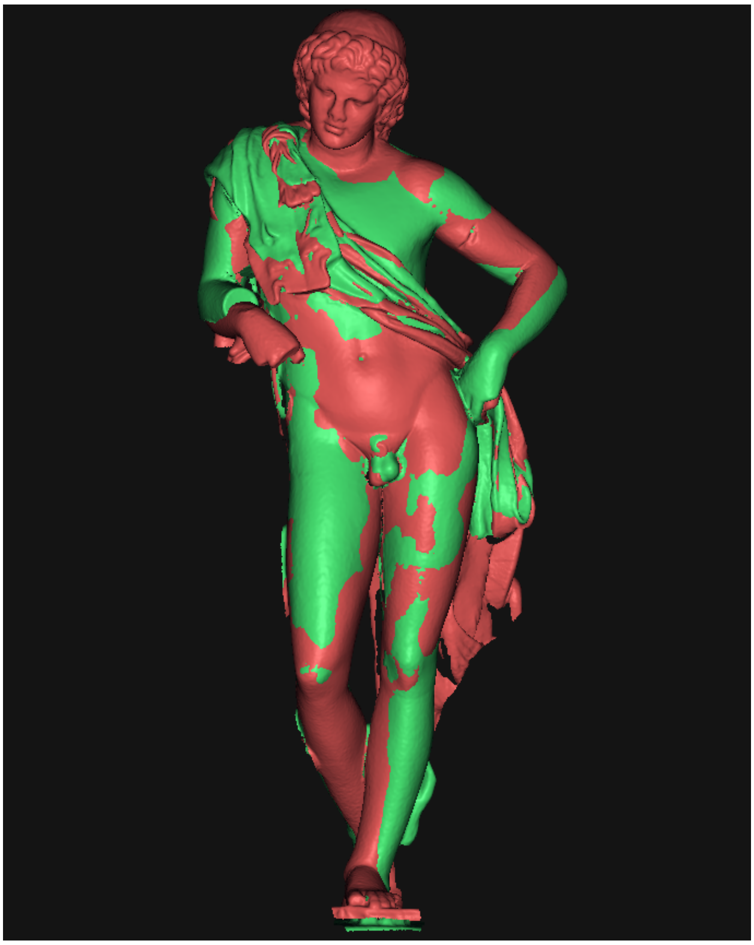


Figure 2.2.3: A demonstration of rigid alignments. Satyr I in red and Satyr II in green.

example, in Fig. 2.3.2(b), nose, chin and some place in forehead are heavily damaged so that it is hard for these parts correspond to "correct" points on face of statue shown in Fig. 2.3.2(a). Therefore correspondence search which includes all pairs of mesh models seems not so fair. In order to handle this problem, a *Region of Interested* (ROI) guided alignment method is further explored.

In this ROI-guided alignment strategy, only well kept parts are counted when alignment implemented. In this *Satyr* heads case, only data above eyes are utilised to calculate the rigid transformation parameters. Thus higher precision will be achieved. Alignment result is shown as Fig. 2.3.2(e).

2.3 Numerical Expression of Shape Differences

Based on the alignment results, we adopt a correspondences matching method based on nearest neighbour point 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. Further more, this kind of distance are visualized by colour map; Statistical Indicators are introduced to achieve objective evaluation.

2.3.1 Difference Definition

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

$$d \doteq \begin{cases} sgn(\mathbf{n_v} \cdot (\mathbf{v}_c - \mathbf{v})) \cdot \|(\mathbf{v}_c - \mathbf{v})\| & \text{if } \mathbf{v}_c \neq \mathbf{v}, \\ 0 & \text{otherwise}, \end{cases} \tag{2.3}$$

where $sgn(\cdot)$ is the sign function. Fig. 2.3.1 illustrates this calculation.

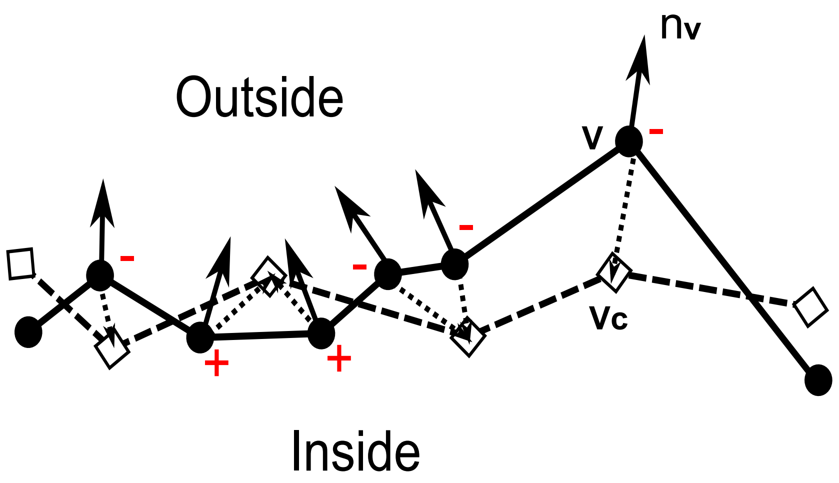


Figure 2.3.1: An illustration of calculating the distance between two shapes, which are denoted with dotted and solid lines respectively. Originally presented in [38] and reproduced here with permission.

2.3.2 Difference Visualization with color-mapping

In order to make comparison result more intuitive and easier to understand, we visualize these signed shape differences similar as [38]. Points are stained according to their corresponding signed shape differences. Thus the distribution of difference (or in another word, dissimilarity) is achieved at the same time when each pair of correspondent points are coloured according to distance.

An example is illustrated in Fig. 2.3.2(f). It is possible to set the threshold of visualization arbitrarily. In our case, dark blue and dark red are assigned to represent minimum and maximum respectively. Zero, marked as green, means two correspondent points overlap completely, in another saying, two objects are exactly same on this spot. Areas where distance beyond threshold will be shown as black. Thus generally speaking, the larger coloured area (especially the green-like area) is, the better two point cloud match and the more similar two objects are.

2.3.3 Numerical evaluation

Besides of the intuitive colour-coding visualization, we still need to quantitatively evaluate the similarities/dissimilarities. Numerical evaluation benefits in multi-pairs comparison and will raise the confidence of assertions under shape comparison.

A naive statistics, *Average Distance* or *AD*, is used as the measurement of dissimilarities between statues in our work. After the ROI-Guided alignment naturally the optimistic correspondence between two point-clouds is setted up and whose average absolute distance reviews the overall extent of dislike between two statues.

Presume there exist point p belongs to set $\{P\}$ representing statue1, and its correspondent point q belongs to set $\{Q\}$ representing statue2, and total number of pairs are N, *Average Distance* are defined as equation. 2.4:

$$AD = \frac{1}{N}\sum_{i}^{N} \|\mathbf{p}_i - \mathbf{q}_i\| \tag{2.4}$$

Finally, we would like to summarize this chapter with a figure to illustrate the pipeline of proposed sculpture comparison method. Fig. 2.3.2 gives an instance.

1. Three dimensional models are constructed via pre-processing;

2. ROI-Guided alignment is applied to achieve optimistic matching between two models; AD is obtained at the same time for further quantitative analysis;

3. Colour-coding figure is generated to visualize difference distribution.

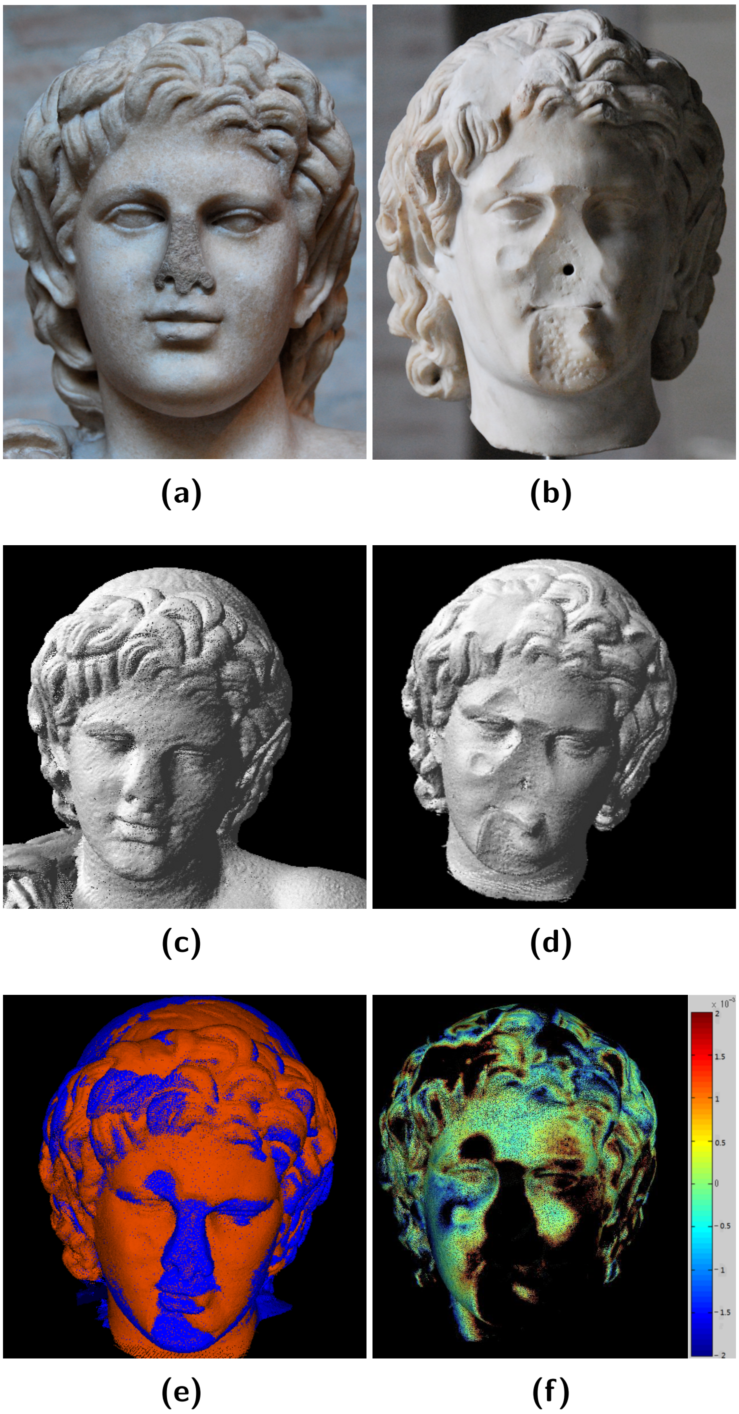


Figure 2.3.2: An example of pipeline of classical sculpture comparison. As shown in (a) and (b) respectively, the head part of two marble statues, *Satyr I* and *Satyr III*, are utilized as target objects. (c) and (d) are the corresponding digital copies. (e) shows the rigid alignment result and (f) 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.

The snow reprints it, as it were, in clear while type alto-relievo. The ornamented grounds of villas which will one day be built here may still preserve some trace of this.

Henry David Thoreau

3 Hypothesis Verification

"Fact" and truth sometimes hide in historical relics themselves rather than words in documentations. Thus it becomes necessary getting sound evidences to support a hypothesis to be sound. There are several hypotheses about classical sculptures waiting for verification, on which similarity affects, so that 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 [13]. In this chapter we try to verify some archaeological hypothesis by sculpture comparison. Based on precision analysis we hope to review information consistent with historical material.

3.1 Precision Analysis & Phased Reproduction

3.1.1 Background and Problem Description

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[1, 39]. 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.

For the process of reproduction, many archaeologists believe that instead of overall copy, ancient craftsmen copy sculptures part by part, since target statues are usually relatively large. But by what kind of evidence can we validate this saying besides just a few words in documentary records? Precision analysis inspires us.

We probably believe that if sculpture parts were first made separately and then assembled together, then there must be some clues showing that the whole sculpture is less a coherent entity. The clues maybe obvious precision distinction or the distortion brought by small miss match on connection joints. Precision visualization will help us with the former issue and ROI-guided alignment will help us with the latter one.

3.1.2 Experiment

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.

In this experiment, we would like to discuss the reproduction process by study the *Resting Satyr* statue. It was created by an ancient Greek sculptor *Praxiteles*, has been found a large number of replicas since the Greek period[1]. Fig. 1.1.1(a), 1.1.1(b) and 2.3.2(b) show three of these copies from the *Glyptothek Museum*, labelled as No.228, 229 and 229A respectively. We relabel them as Satyr I, II and III for convenience.

First, let us start with the precision analysis of the statue copies.

Fig. 2.3.2 demonstrates the shape difference between the heads of *Satyr I* and *Satyr III*. Points are stained according to their corresponding signed 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. 2.3.2(f) and Fig. 3.1.4, 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.

Besides, as shown in Fig. 3.1.1, 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.

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. 3.1.2 shows the comparison.

We observe that separately aligned result achieves more accurate matching than the overall registered one. A highly reasonable explanation for this phenomenon is that

[1]According to the study in [40], 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.

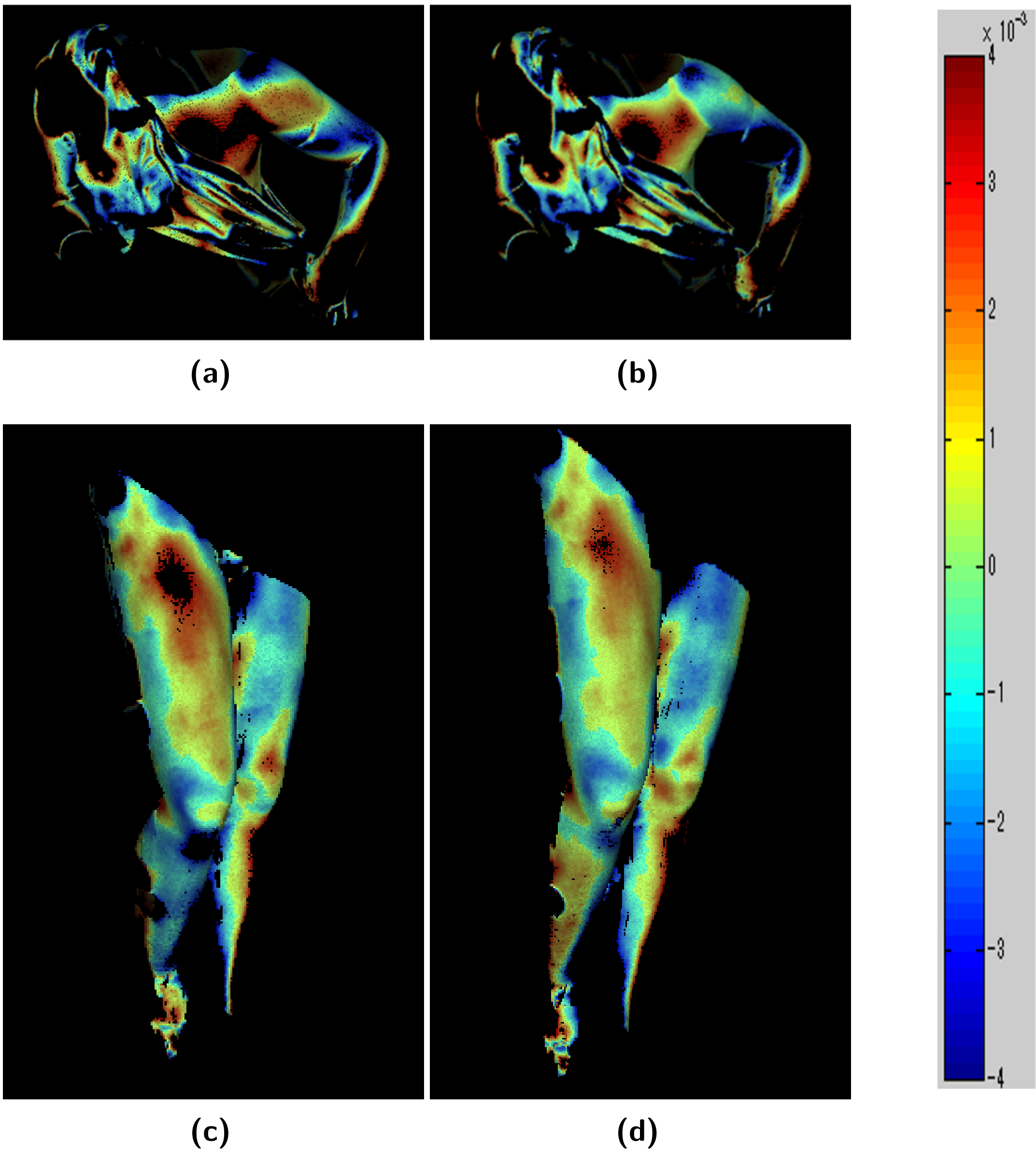


Figure 3.1.1: Visualization of dissimilarities between *Satyr I* and *Satyr II*. Two different strategies are used during the comparison: (a) and (c) show the shape differences based on overall alignment, while (b) and (d) are better matching results where the front part are of higher priority during alignment. This supports the assumption that the front part of statues got more attention during the copy process in Roman period.

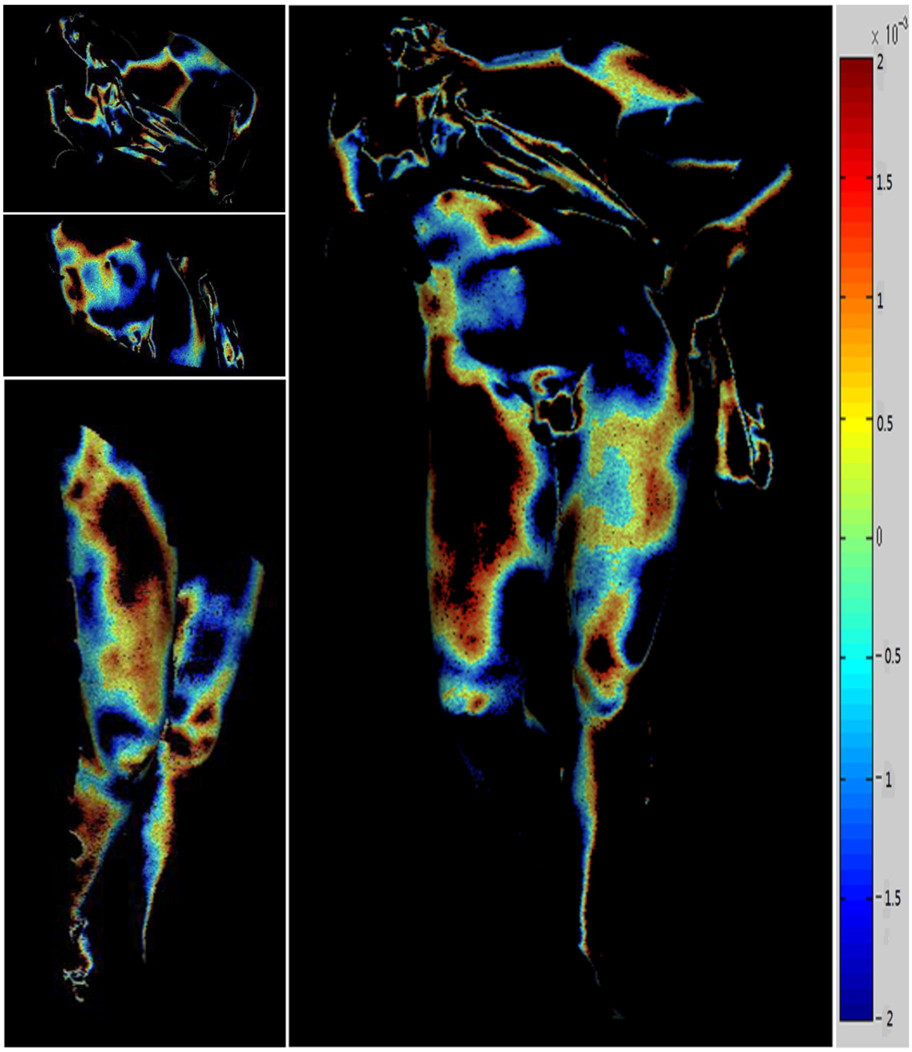


Figure 3.1.2: Shape dissimilarities based on locally and overall alignment. the three relatively smaller blocks are matching results based only on the part of chest, belly and legs respectively, while the largest block shows the result using overall registration.

originally important components of a statue were copied respectively and then assembled into one, rather than copied the entire statue at one time. This is not the case, apparently, many statue copies also show the same phenomenon. Below shows one more instance.

The comparison results shown in Fig. 3.1.4 are that of two marble copies of "Doryphoros" in Fig. 3.1.3. They were originally created by the famous sculptor: *Polykleitos*.

Interestingly we confirm that at least in the case of "Doryphoros", not only the head and the feet but also the hands were copied precisely by taking many points. This is fruitful and taken for granted because the lengths of hand-parts (width of finger, palm, length from the finger tip to the elbow etc.) were used as units of measurement in antiquity.

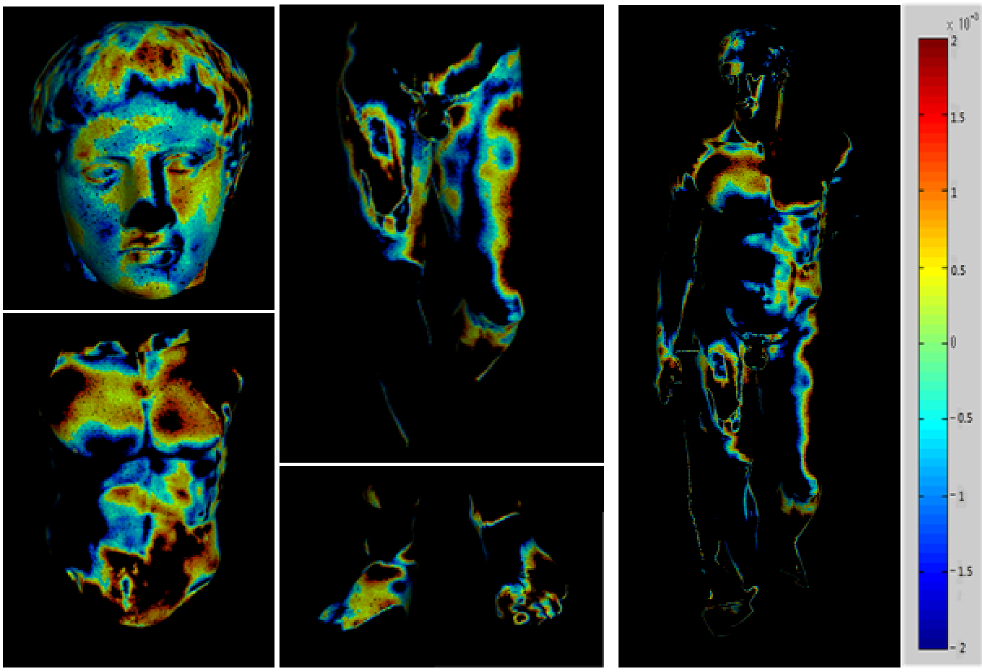
3.1.3 Assertion

In ancient Roman times, the reproduction of classical sculpture had quite high probability to be carried out part by part, rather than as a whole in the same time. This process might be caused by the limitation of the sculpture's size.

Our comparisons revealed that some good Roman copies are incredibly precise, with differences of only a few millimetres between some pairs; heads, feet, and hands were usually copied more precisely than the other parts.In addition, coherent with common sense, the frontal parts of sculptures seems have higher precision than back.

(a) (b)

Figure 3.1.3: Two statues of "Doryphoros": (a) *Doryphoros6011*, copy of Polykleitos's Doryphoros in Naples; (b) *Doryphoros Minneapolis*, copy of Polykleitos's Doryphoros in plaster cast, Munich. For convenience in following discussion, we rename (a) as Dory6011 and (b) as DoryM.



(a) **(b)**

Figure 3.1.4: Visualization of dissimilarities, comparing two copies: *Dory6011* and *DoryM*.Shape dissimilarities based on locally and overall alignment. The left four relatively smaller blocks are matching results based only on the part of head, torso, legs and feet respectively, while the largest block shows the result using overall registration. Referring to the colour bar right side, clearly we may notice that separate alignment achieved larger overlaps than overall one, which give a hard evidence of phased production theory.

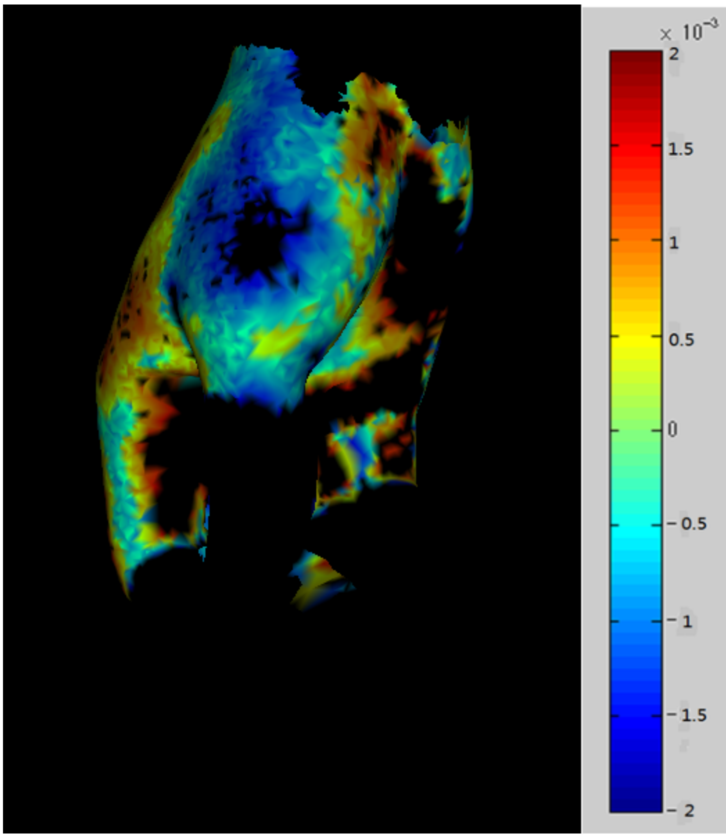


Figure 3.1.5: The comparison result of right hands of two copies of "Doryphoros" under the precision threshold of 2 millimetres. Large green-like areas reveal incredibly precise of hand copy, when they are treated as separate aligned parts. This shows that hands were usually copied very precisely as well as hands were separately created.

3.2 "Who Made This Sculpture?"

3.2.1 Background and Problem Description

According to Pliny the Elder, five bronze statues of Amazons were built in 5th-century BC in a long lasting competition between the artists Polykleitos, Phidias, Kresilas, Kydon and Phradmon, and the first rank was assigned to Polykleitos, the second to Phidias, the third to Kresilas.

There are three statuary types (*Mattei-type*, *Sciarra-type* and *Sosicles-type*) representing a wounded Amazon known to us. These types, each well represented by numerous Roman copies and heads, are identified with Polykleitos, Phidias and Kresilas. As for Mattei type Amazon, the archaeologists attribute it to Pheidias, but as for the other two types the discussion is still continuing.

In our study, we would like to that give a approach to that controversy by finding the attribution of the statue of *"Wounded Amazon"* shown in Fig. 3.2.1a. It is a Roman marble copy from a Sciarra-type bronze original. The sculptor's name of the original, Kresilas or Polykleitos, if is able to be determined with some sound evidence, then the attribution problem of both *Sciarra-type* and *Sosicles-type* will be solved.

Fortunately, it is not totally clueless to deduce a work's attribution. 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[13]. Let us assume that the copy well represented the original. Thus we can derive the relation between originals from comparing two copies.

Here we decided to employ the same method as [13] for this study. Comparing this "Amazon Sciarra" with works of Polykleitos or works of Kresilas, we hope to find highly similar parts so that to prove that some models are reused to construct different characters. If the attribution of the correspondent character (statue) is happened to be known, we may claim that "Amazon Sciarra" shares same sculptor with that

(a) **(b)**

Figure 3.2.1: Two statues for attribution inference: (a) *Amazon Sciarra* in Copenhagen; (b) *Diadumenos* in Athens. (a) is also called "*Kresilas' Amazon*", because some archaeologists believe it is after Kresilas.

correspondent statue. In addition, as Polykleitos's his works are also criticized because they were "from one model" (paene ad unum exemplum), said Pliny, it gives us a direct hint to start comparing.

3.2.2 Experiment

First we compare this Amazon with a representative work of Polykleitos.

We find that the *Diadoumenos in Athens* statue by Polykleitos, shown in Fig. 3.2.1b, seems have same feet pose with "Amazon Sciarra", especially extremely similar left foot. (Right foot are not counted in this study because of its restoration.)

The comparison results of the two left feet of *Diadoumenos* and *Amazon Sciarra* are shown in Fig. 3.2.2. Let us check how precise the similarity reaches.

Notice that color area represents distance within 2 millimetre. 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.

3.2.3 Assertion

Regarding the century-long discussion about the famous three Amazon statues, each created by Polykleitos, Pheidias or Kresilas but has never securely attributed, we found that the foot forms of the Sciarra type Amazon closely match those of the Diadoumenos by Polykleitos. These results indicate that it is the Sciarra Amazon highly possibly was created by Polykleitos.

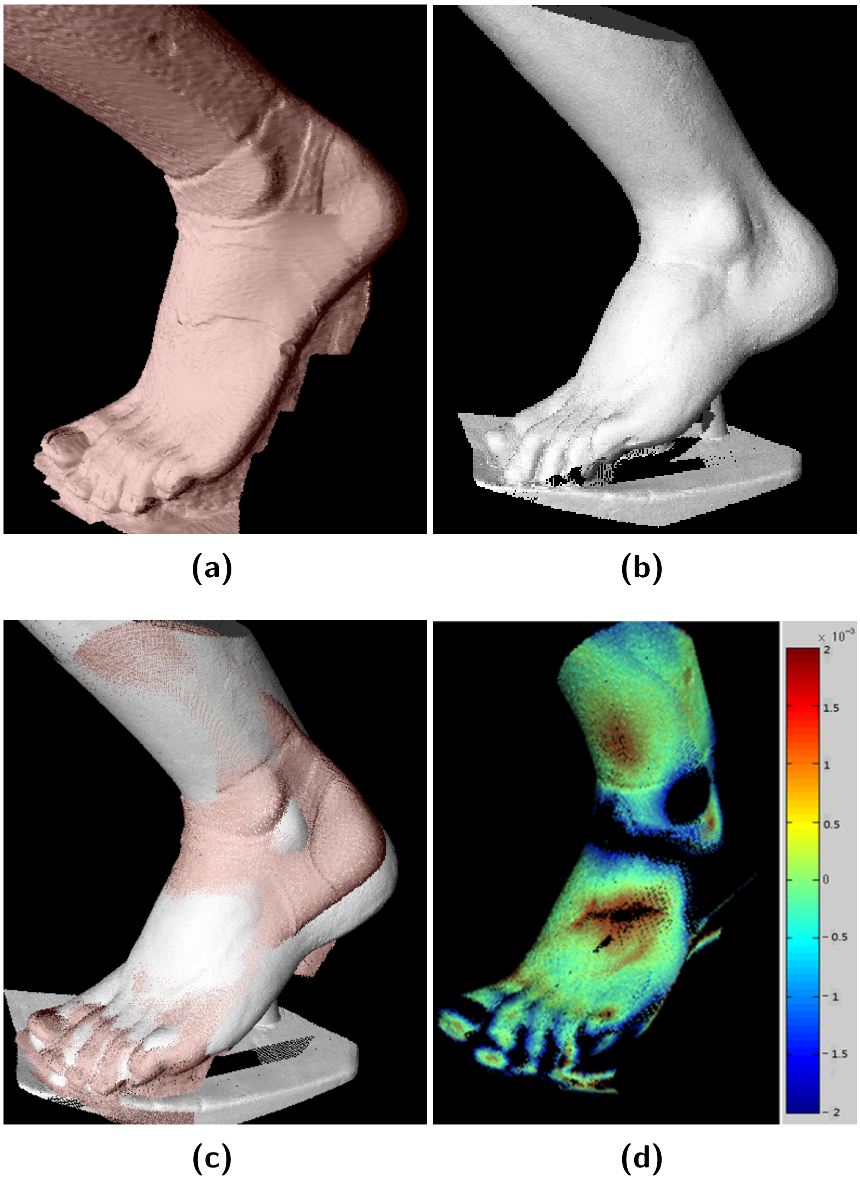


Figure 3.2.2: Comparison of the two left feet from two different statues— "Amazon Sciarra" and "Diadoumenos in Athens". (a) and (b) show the two target shape; (c): result after rigid alignment; (d): visualization of the shape difference.

Stone does not decay, and so the tools of long ago have remained when even the bones of the men who made them have disappeared without trace.

Robin Place

4 Discussion: Inference Based on Comparison

Colour code visualization of two statues enables us to distinguish the millimetre differences. This helps to verify a hypothesis which could be attributed to a similarity problem. Numbers seem can not help to telling us more stories if we take good use of the precise comparison results. In this chapter, we would like to take a step forward and discover the unknowns hidden in those like-unlike relationships.

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

Figure 4.1.1: Four statues of Polykleitos: (a) *Doryphoros6011* in Naples; (b) *Doryphoros Minnerpolis*, in Munich; (c) *Diadumenos* in Athens;(d) *Amazon Sciarra* in Copenhagen. For convenience in following discussion, we rename (a) as Dory6011, (b) as DoryM, (c) as DiaA, (d) as Amazon.

4.1 Polykleitos' Models

Polykleitos was an ancient Greek sculptor in bronze of the fifth century BCE. He is considered one of the most important sculptors of classical antiquity. Polykleitos was famed for his statues of athletes and Pausanias names six such statues dedicated in Olympia, but his works were also criticized because they were "from one model" (paene ad unum exemplum), said Pliny. Usually these words are interpreted as referring to his monotonous style, but in this section, we hope to research deeply about the reason of the remark "from one model" and whether he literally did use one model for different statues and further infer the rules of model usage in sculpture works of Polykleitos.

The targets for this research are four statue copies of Polykleitos's. Fig. 4.1.1.

Doryphoros6011, Museo Archeologico Nazionale di Napoli, inv. 6011, is a well-preserved Roman period copy of the Doryphoros of Polykleitos in the Naples National Archaeological Museum. *Doryphoros Minnerpolis* is a copy of Roman period copy of the statue in marble, conserved in Museum of Casts Classic sculptures Munich. Doryphoros arouse people's attention because this work were treated by Polykleitos as a demonstration of his written treatise, entitled the "Kanon" (or Canon), exemplifying what he considered to be the perfectly harmonious and balanced proportions of the human body in the sculpted form. *Diadumenos* in Athens and *Amazon Sciarra*, as we talked in last chapter, are also representative works of Polykleitos.

4.1.1 New Discoveries

As introduced above, a three-dimensional laser scanner with an accuracy of ±50μm was used to scan statues and, after superimposing two of the resulting digital forms, the distance between the two could be visualized in a colour code which enables us to distinguish millimetre differences. After pair-wise comparison among those four statues we obtained results shown as follows.

DoryM vs. DiaA

Taking account of the missing of toes of DoryM's right foot, only left foot is taken into consideration. Visualization threshold of distance is setted as 2 millimetres. In Fig. 4.1.2, large area of black, no matter entire foot alignment or only toes alignment, tells the fact that DoryM and DiaA do not match neither in foot nor toes part. This result affirm us that Polykleitos used two different foot models when he created DoryM and DiaA.

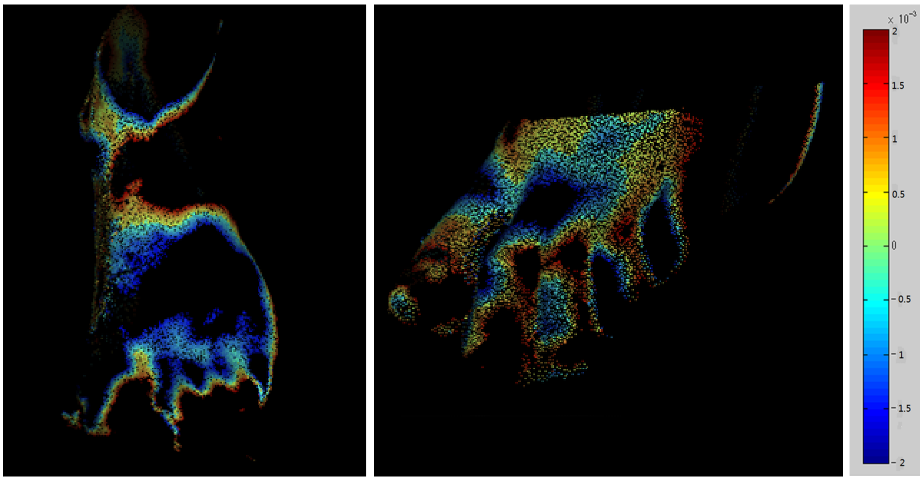


Figure 4.1.2: The comparison between DoryM and DiaA in feet and toes: (a) left feet; (b) toes only; all results shown within 2-millimetre threshold.

Dory6011 vs. DiaA

Faces, feet, toes and legs are compared separately.Visualization threshold of distance is setted as 2 millimetres. From Fig. 4.1.3 we can say that: 1) faces match well except right cheek, which in some extant prove the criticism of monotonous style; 2) large area of black in foot and toes shows that DoryM and DiaA do not match neither in foot nor toes part. This result affirm us that foot model of Dory6011 and that of DiaA were also different.

DoryM vs. Amazon

Same reason as mentioned above, as toes of DoryM's right foot are missing, only left foot is taken into consideration. Visualization threshold of distance is setted as 2 millimetres. In Fig. 4.1.4, large area of black of foot comparison result, tells the fact that DoryM and DiaA do not match in left foot. This result affirm us that Polykleitos made different foot models for DoryM and Amazon.

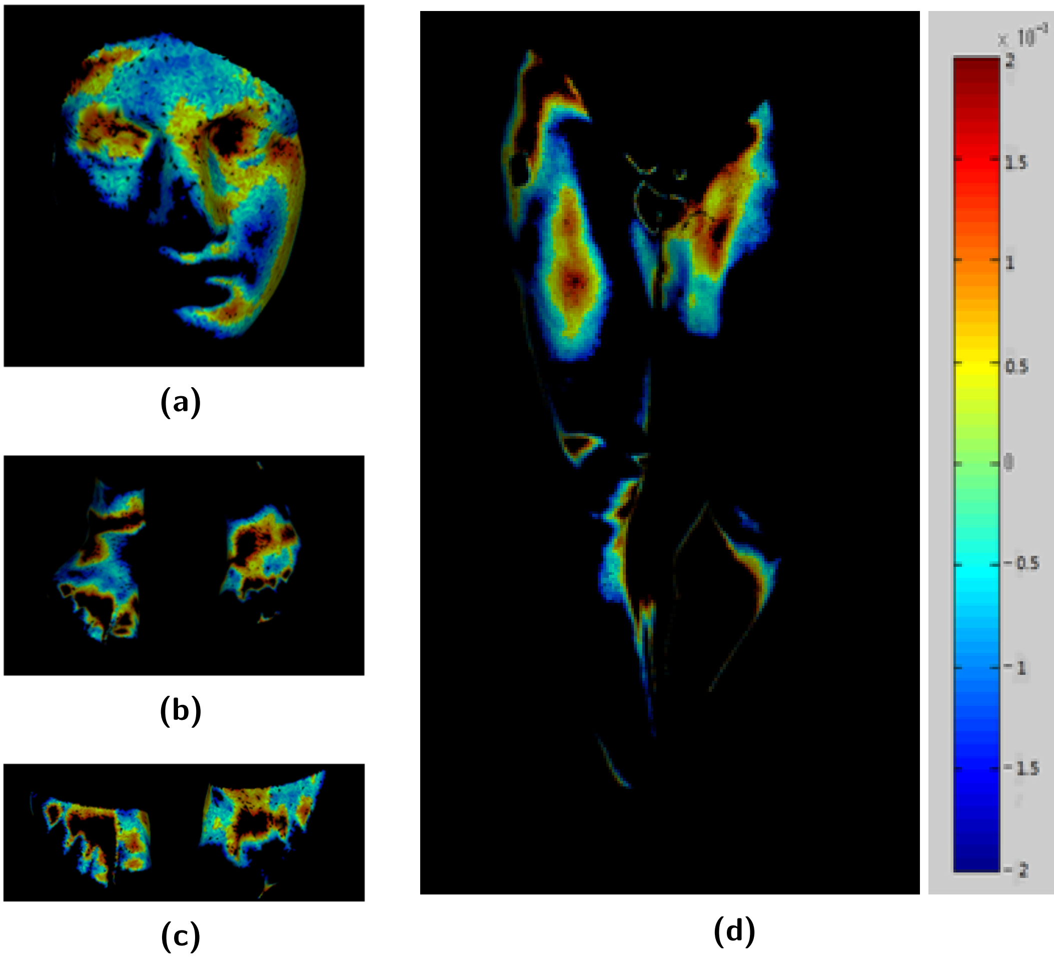


Figure 4.1.3: Visualization of dissimilarities between *Dory6011* and *DiadumenosA*. Faces, feet, toes and legs are compared separately. All results shown within 2-millimetre threshold.

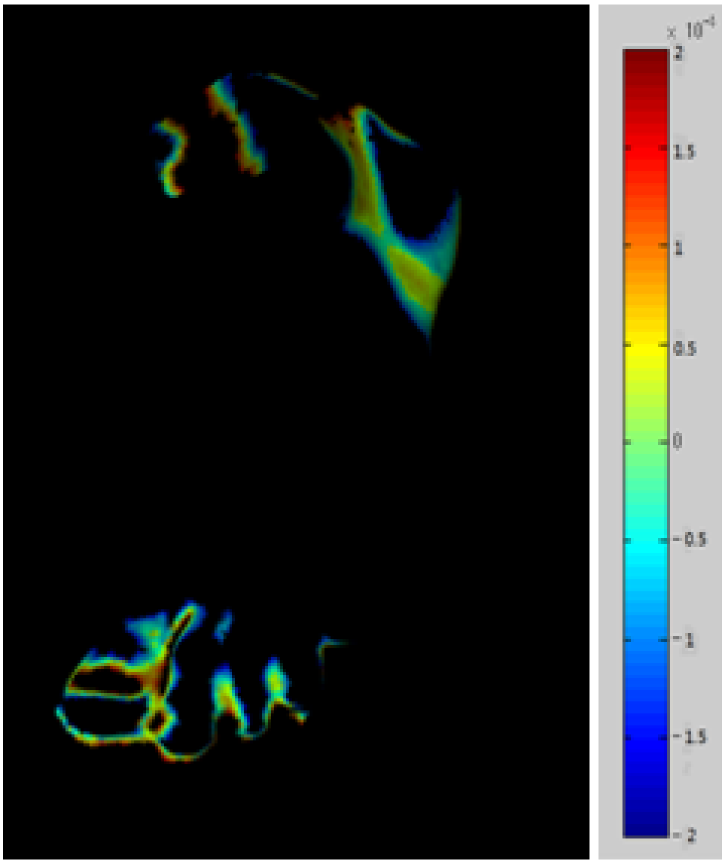


Figure 4.1.4: DoryM vs. Amazon. Left foot comparison results shown 2-millimetre threshold. Large area of black indicates they do not match well.

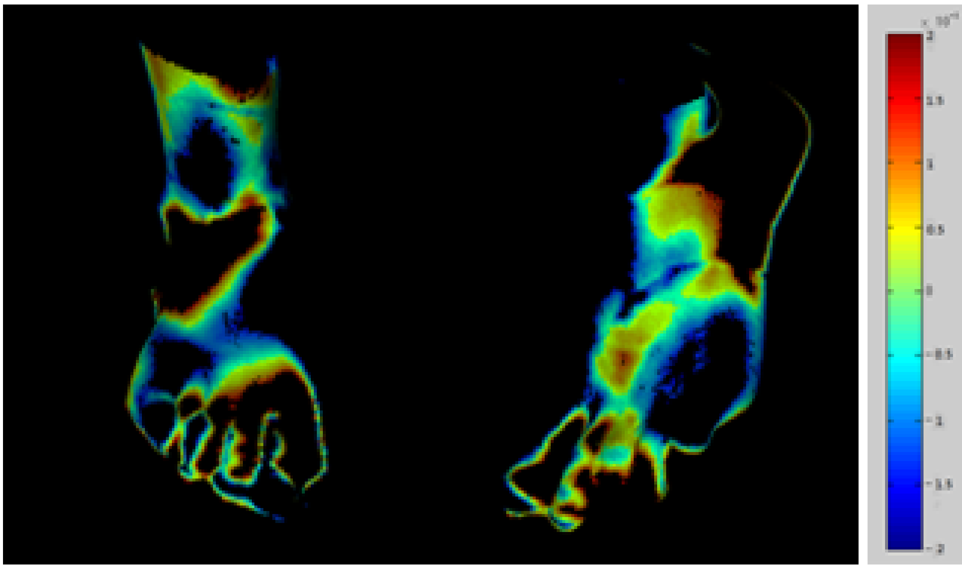


Figure 4.1.5: Dory6011 vs. Amazon. Feet comparison results shown 2-millimetre threshold. Insteps seem match well but toes do not.

Dory6011 vs. Amazon

Similarly, the feet comparison result are shown in Fig. 4.1.5. Visualization threshold of distance is setted as 2 millimetres. Green-like area is still not large enough to claim that the two feet match well. Conversely, we tend to believe the foot models for Dory6011 and Amazon are different as well.

Conclusion

From the discussion above, we notice that foot forms of Doryphoros do not match those of Sciarra type Amazon nor Diadoumenos in Athens, whereas foot forms of the two latter ones match well.

4.1.2 Traces in historical material

Doryphoros of Polykleitos, the Canon, was the most renowned ancient treatise on art. The aim of the Canon, was not simply to explain a statue but also to demonstrate what "beauty" is. The secret lay in the mastery of symmetria, the perfect harmony of all parts of the statue to one another and to the whole[41].

Polykleitos's idea of symmetria and the pursuit of the to beauty and to perfect was probably influenced by exposure to the ideas of Pythagoras of Samos (active in the late sixth century B.C.) and of his followers. Pythagoreans saw reality as having a pattern of oppositions.[42] Aristotle presents the following list of these binaries: Aristotle, Metaphysics, I.5.986a22: "Members of this school say there are ten principles, which they arrange into two columns of cognates, thus: limited and unlimited; odd and even; one and plurality; right and left; male and female; rest and movement; straight and curved; light and darkness; good and bad; square and oblong."

Modern scholars have seen in Polycleitos's work a similar balance of opposites. Three of these pairs are easily detected in the Doryphoros: right/left, rest/movement, and straight/curved and seems rest of those pairs appeared in Doryphoros's works at some extant.

Interestingly enough, archaeologists date the Doryphoros C. 450-440 BC and the Diadoumenos and the Amazon C. 430 BC, namely, about 10-20 years later than Doryphoros. The Diadoumenos represents a youth younger than the Doryphoros. Pliny described the former "soft-looking youth" and the latter "adult-looking youth". Maybe Polykleitos created the foot model of soft-looking youth/female type (eg. for Diadoumenos and Amazon) separately from the adult male type (eg. for Doryphoros).

4.1.3 Inference

According to the discussion in Chapter 3, we see that the foot forms of the Sciarra type Amazon closely match those of the Diadoumenos after Polykleitos. Conversely, they do

(a) *DoryPQ* **(b)** *Dory6412* **(c)** *Dory6011* **(d)** *DorypM*

Figure 4.2.1: Four head statues of "Doryphoros". (a) and (b) are "herms", only the head is represented on a pillar; (c) and (d) are head parts of whole body statues. The former were exhibited on the eye level, but the latter, being on the top of a statue, were about 2m high.

not match those of his canonical Doryphoros. These results indicate that: 1) he kept models in his workshop to reuse for other statues, and 2) he distinguished the foot form of the "manly" Doryphoros (Pliny NH 34.55: viriliter puerum) from that of the "tender" Diadoumenos (molliter iuvenem) and cast the female feet from the latter. If he adopted the Diadoumenos' model to his Amazon, maybe he did the same to his boy athlete statues and his Doryphoros' model to his adult athletes.

4.2 Copy Reliability Ranking

Unfortunately neither the original Doryphoros of Polykleitos nor the treatise have yet been found; it is widely considered that they have not survived from antiquity. However, several Roman copies luckily survive to convey the essential form of Polykleitos' work, though they were of varying quality and completeness.

Facing with difficulty of the uncertain of original form and the variety of copies, therefore, it becomes important and necessary to distinguish the reliability of the existing copies, taking into account of flawlessness, fineness and completeness.

Moreover, dealing with amounts of copies, a ranking mechanism with certain number, such as a"points system" will be helpful for evaluation in a great deal.

We start with four Doryphoros copies (shown in Fig. 4.2.1) in different quality, different material and even different forms as a trial.

DoryPQ, shown in Fig.4.2.1a, shorted for Doryphoros (Herm), with the signature of Apollonios, Museo Archeologico Nazionale di Napoli, inv. 4885, made of bronze, 54cm height, considered by many scholars to be an almost flawless replica of the original Doryphoros head.

Dory6412, shown in Fig.4.2.1b, shorted for Doryphoros (Herm) in Museo Archeologico Nazionale di Napoli, inv, 6412, made of marble with 36cm height, are a sample of Doryphoros head with just OK copy quality.

Dory6011, shown in Fig.4.2.1c, shorted for Doryphoros (Statue) in Museo Archeologico Nazionale di Napoli, inv. 6011. It is perhaps the best known copy which was excavated in Pompeii.

DorypM, shown in Fig.4.2.1d, is a plaster copy of Doryphoros Minneapolis (Statue), in Museum for Casts of Classical Sculpture in Munich. Largely complete with the exception of the lower left arm and fingers of the right hand, Doryphoros Minneapolis (height 1.96 m) has been variously dated to the period 120-50 BCE, as well as to the mid-Augustan period.

Because of the difficulty of original loss, we assume the one with smallest distance to others has the highest reliability. This assumption is derived from a common sense that one copy which likes all the others should hold the average shape among the copies group. In the other words, the most "average" one should escape flaws brought by copy process and should be the nearest to the original in shape. Therefore, we implement the mechanism that first pair-wisely compare the heads, colour-coding the distances of the two surfaces (like our comparisons till now) and rank their reliability as a copy with a number. *AD, Averge Distance*, introduced in Chapter 2, used as the measurement of dissimilarities between statues, is borrowed here directly to express the points of reliability. Of course higher AD means lower reliability points.

4.2.1 New Discoveries

Starting with DoryPQ, the fine bronze herm, we compare it with other copies, because it is assumed to be the most reliable copy. Two different strategies are used during the comparison: first as whole heads and then only the frontal parts. Comparison result shows in Fig. 4.2.2. AD analysis shows in Table 4.2.1.

Table 4.2.1: AD of DoryPQ vs. Others (Unit: mm)

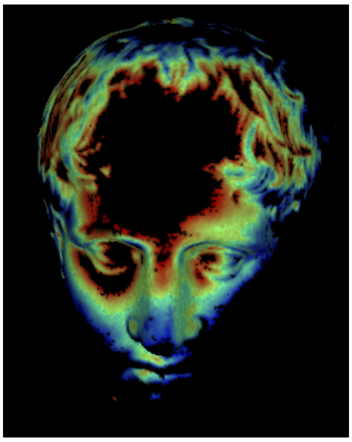
DoryPQ vs.	Head	Face
Dory6412	1.539	0.947
Dory6011	1.582	1.217
DoryM	1.371	1.220

Similarly, we compare the other herm, Dory6412, to the other Doryphoros heads and frontal faces. The difference visualization shows in Fig.4.2.3 and AD analysis shows in Table 4.2.2.

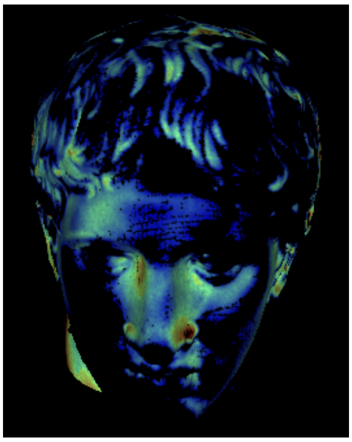
Table 4.2.2: AD of Dory6412 vs. Others (Unit: mm)

Dory6412 vs.	Head	Face
DoryPQ	1.539	0.947
Dory6011	1.484	1.157
DoryM	1.151	0.975

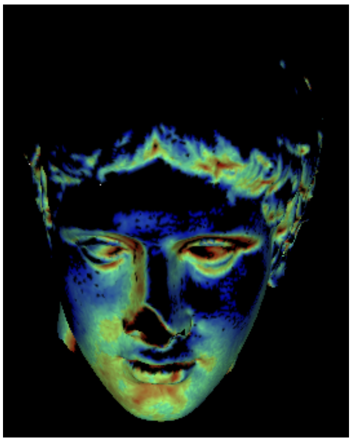
Pair-wise comparison among four Doryphoros and AD analysis are shown below. Table 4.2.3 concludes the AD based on front faces alignment while Table 4.2.4 shows



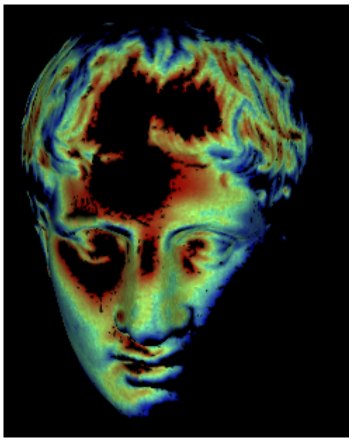
(a) DoryPQ vs. Dory6011



(b) DoryPQ vs. Dory6412

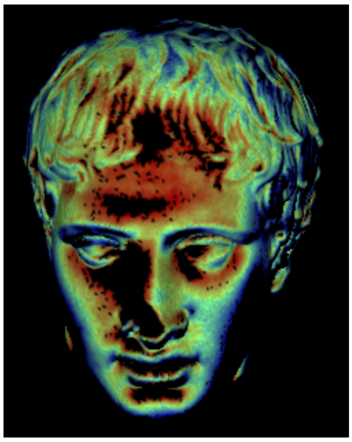


(c) DoryPQ vs. DoryM



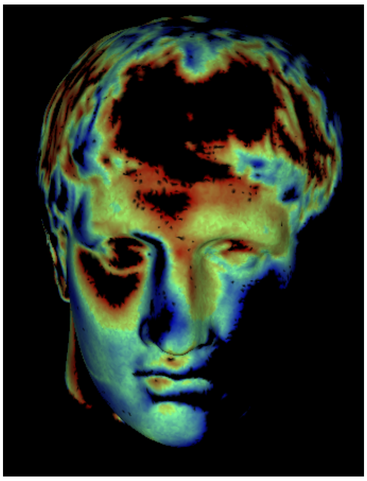
(d) DoryPQ vs. Dory6011

(e) DoryPQ vs. Dory6412

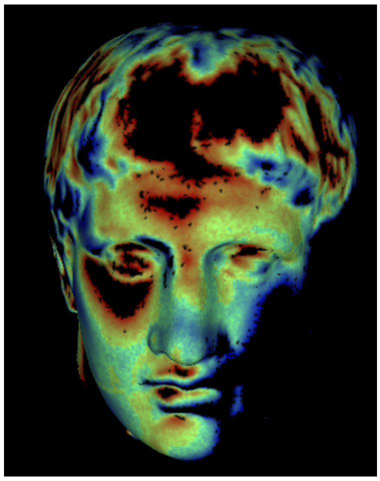


(f) DoryPQ vs. DoryM

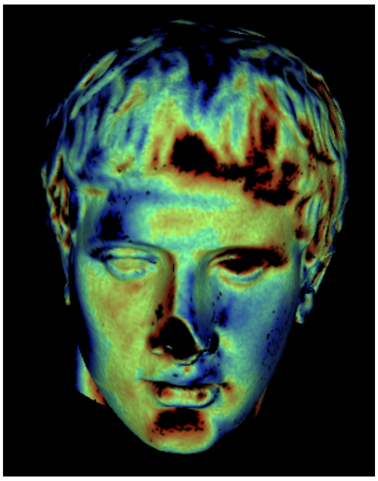
Figure 4.2.2: DoryPQ vs. others. Two different strategies are used during the comparison: (a)-(c) show the shape differences based on whole head alignment, while (d)-(f) are matching results where only the front parts are taken into account.



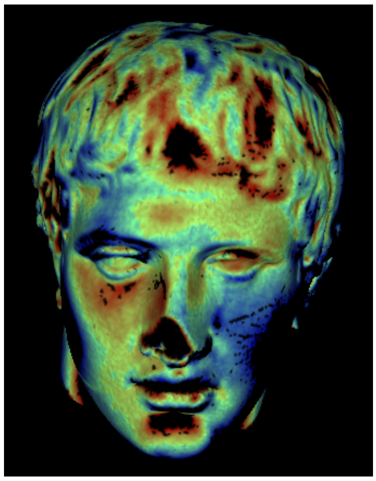
(a) Dory6412 vs. Dory6011



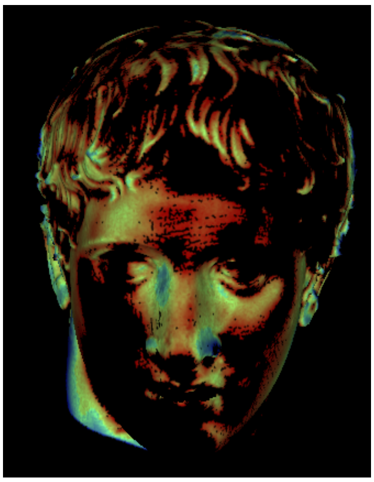
(d) Dory6412 vs. Dory6011



(b) Dory6412 vs. DoryM



(e) Dory6412 vs. DoryM



(c) Dory6412 vs. DoryPQ

(f) Dory6412 vs. DoryPQ

Figure 4.2.3: Dory6412 vs. others. Two different strategies are used during the comparison: (a)-(c) show the shape differences based on whole head alignment, (d)-(f) are are matching results where only the front parts are taken into account.

that of whole head. We choose the sum of AD of a certain sculpture to others as the overall assessment for its distance to the others. That means the lower "Sum of AD" a sculpture get, the higher reliability as copy it has.

Table 4.2.3: AD of Frontal Faces (Unit: mm)

Face	DoryPQ	**Dory6412**	Dory6011	DoryM
DoryPQ	0	0.947	1.217	1.220
Dory6412	0.947	0	1.157	0.975
Dory6011	1.217	1.157	0	0.955
DoryM	1.220	0.975	0.955	0
Sum of AD	3.384	**3.079**	3.329	3.15

Table 4.2.4: AD of Whole Heads (Unit: mm)

Head	DoryPQ	Dory6412	Dory6011	**DoryM**
DoryPQ	0	1.539	1.582	1.371
Dory6412	1.539	0	1.484	1.151
Dory6011	1.582	1.484	0	1.261
DoryM	1.371	1.151	1.261	0
Sum of AD	4.492	4.174	4.327	**3.783**

4.2.2 Observation

1) The bronze herm DoryPQ matches best with the marble herm Dory6412. Table 4.2.1.

It suggests that the herm may have been executed more precisely than the head part of a whole statue. It is reasonable, because people saw the herm head more closely than the head of a whole statue; the former were exhibited on the eye level, but the latter, being on the top of a statue, were about 2 metres high.

2) The comparison results tell us that bronze head DoryPQ is not the most reliable copy.

The bronze head DoryPQ should have suffered slight distortion under the ashes of Mt. Vesuvius. (It was found in Herculaneum, destroyed in AD 79 by the explosion of Mt. Vesuvius, like Pompei.) Although the bronze head DoryPQ is a excellent copy regarding the representation of hair locks and other details, the marble head (Dory6412) is more reliable as for the scull's form.

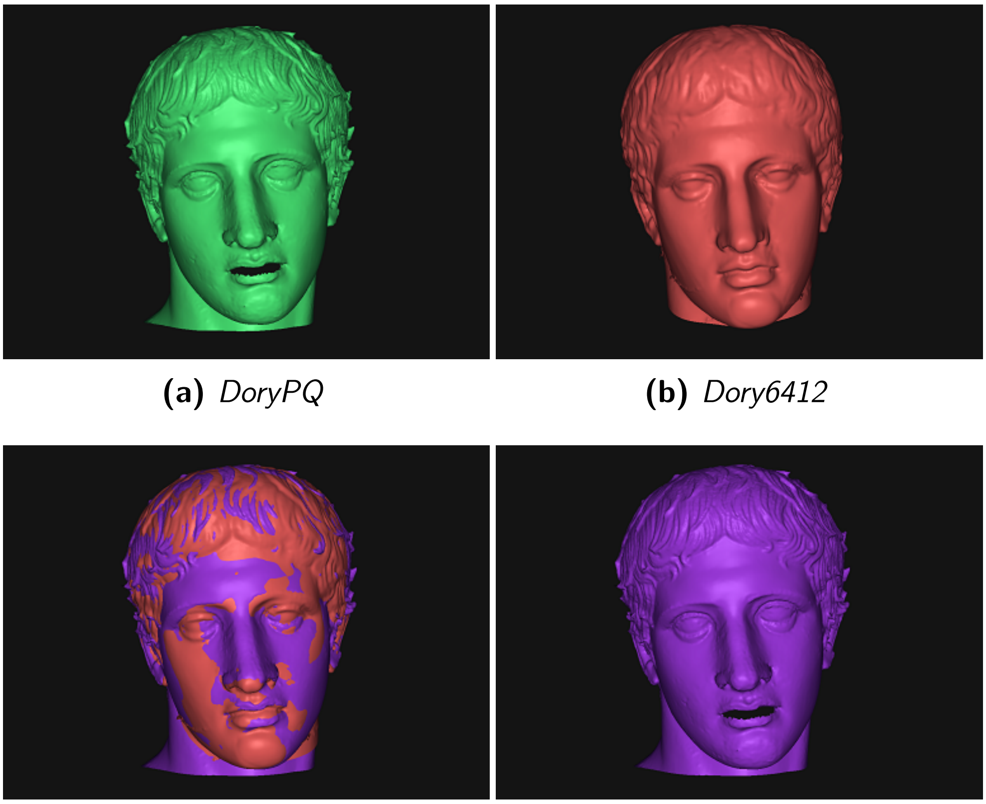
3) Reliability rank changes when taking different parts(whole head/just front face) into consideration.

Table 4.2.3 shows herm Dory6412 has the "best" face while Table 4.2.4 shows statue DoryM has the "best" head. However perhaps herm should have higher priority than statue. Herm heads were located in lower position than the heads of whole statues and, as a result, seen closely; besides, the viewers attention should have concentrated on the face, because there was only the heads.

4.2.3 Discussion

1) The comparisons based on Dory6412/DoryM show more close similarity with other heads, by taking different points, we'd better use that head as the base of the comparisons and calculations of reliability.

2)It would be much better if we create an "ideal model" combining the scull's form (the forehead, the nose line, and the eye positions) of Dory6412/DoryM and the details of DoryPQ.



(a) *DoryPQ* **(b)** *Dory6412*

(c) Deforming **(d)** New model

Figure 4.3.1: New model creation. (a):DoryPQ, a bronze herm with fine details but shapely unlike the original; (b): Dory6412, a marble herm proved to has the best face in shape; (c): the alignment via affine ICP to deform DoryPQ to fit Dory6412; (d) the created new model which preserves the details of DoryPQ and has the spacial shape of Dory6412.

4.3 Standard Construction

From the discussion above, we notice that herm Dory6412 has the "best" face while statue DoryM has the "best" head. Either of them preserved the original shape yet failed to keep fine details as the bronze herm DoryPQ. An idea comes naturally that to create an "ideal model" combining the scull's form (the forehead, the nose line, and the eye positions) of Dory6412/DoryM and the details of DoryPQ. This model will be regarded as the standard that with others will compare and get their reliability points.

Table 4.3.1: AD Analysis of New Models (Unit: mm)

	New model 1		New model 2	
AD	Face	Head	Face	Head
Dory6011	1.041	1.490	1.022	1.374
Dory6412	0.647	0.771	0.748	0.908
DoryM	0.815	0.954	0.675	0.845
Sum of AD	2.503	3.215	2.445	3.127

4.3.1 New Models

In order to create an new model combining two copies, our basic mechanism is to deform the fine model to fit the course but shapely correct one.

Taking Dory6412 and DoryPQ as an example, we try to create the new model which has the scull's form of Dory6412 while keeping the fine feature of DoryPQ. In this process, we apply an affine variant of ICP,[22] to make DoryPQ (bronze) transformed to Dory6412 (marble). We regard this deformed statue as our new model acting as the base in comparison.

Fig. 4.3.1 illustrates a process of how model DoryPQ deform to model Dory6412, in another word, how new model is created. The new model combines DoryPQ and DoryM is made in the same way.

4.3.2 New Model Test

Similar with what have done so far, we compare the "new models" with other copies, to inspect whether those models are experimentally relatively ideal. Two different strategies are used during the comparison: first as whole heads and then only the frontal parts. Comparison result based on two new models show in Fig.4.3.2 and Fig.4.3.3

Table 4.3.2: Scaling of Dorys (proportion to Dory6412)

Dory6412	DoryPQ	Dory6011	DoryM
1	0.9791	1.0351	1.0055

respectively. The deformation of DoryPQ to new models also shows in these figures. AD analysis of them are summarized in Table 4.3.1.

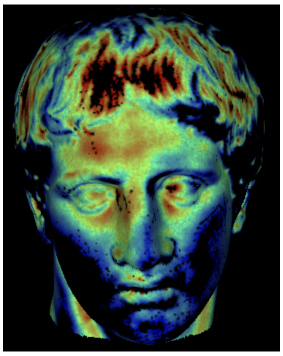
It is obvious that the best replica goes to Dory6412 by giving face part the higher priority while changes to DoryM when taking whole head into account. This problem make it necessary to build new model basing on both of them. After reliability inspection, both of the two new models, (DoryPQ + Dory6412) and (DoryPQ + DoryM), are adequate as the "standard" for the form comparisons and then we can use the AD value as the indicator of the reliability of each head.

We have discussed the possibility of creating new models combining two heads and examined their qualities. They are based on this preliminary: each head sculpture should be used as exactly what they are; in they other words, transformation in any sense should be excluded. However, this restrict seems over strict in this copy reliability assessment, at least size of head should not affects the evaluation of quality of a copy. This situation inspires us that perhaps applying scale normalization of all targets before comparison will make sense more adequately.

For size normalizing, we apply an variant ICP, the classical ICP plus scaling, introduced in [43]. The best scale is estimated along with the other factors of translation and rotation.

In our head copy ranking, we set Dory6412 as the normalizing standard and find the scaling as shown in Table 4.3.2.

Obviously DoryM and Dory6412 are similar in size and are average among those 4 heads, which gives an explanation of their top positions in head ranking without size

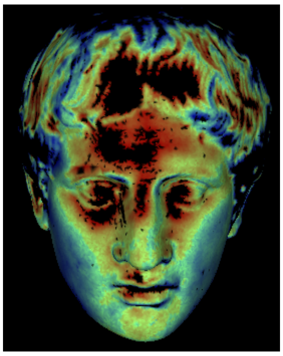


(a) New1 vs. Dory6011

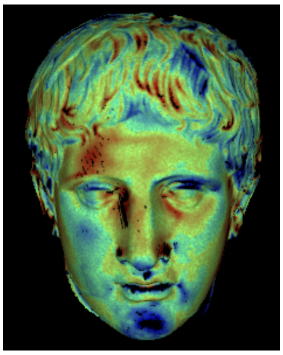
(b) New1 vs. Dory6412

(c) New1 vs. DoryM

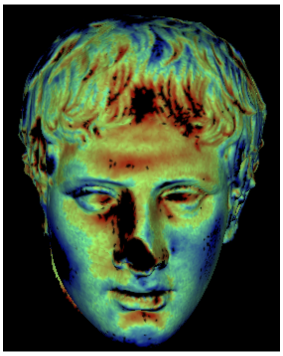
(d) New1 vs. DoryPQ



(e) New1 vs. Dory6011



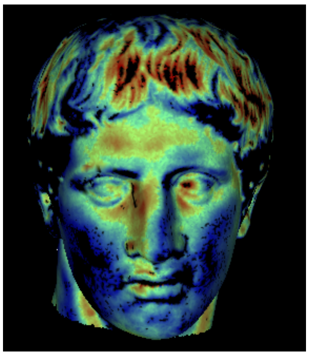
(f) New1 vs. Dory6412



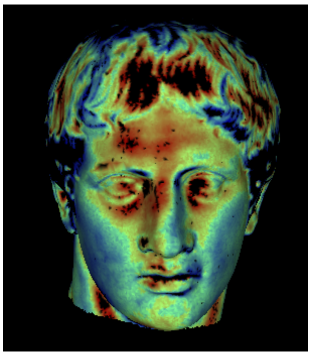
(g) New1 vs. DoryM

(h) New1 vs. DoryPQ

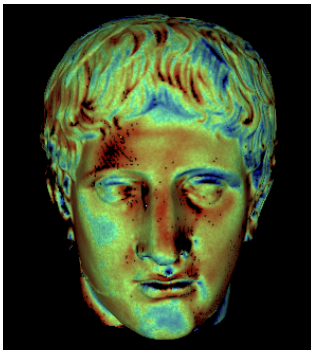
Figure 4.3.2: New model 1 vs. others. New model combines DoryPQ and Dory6412. (a)-(d) show the shape differences based on whole head alignment, while (e)-(h) are matching results where only the front parts are taken into account.



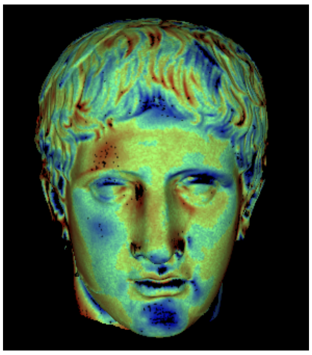
(a) New2 vs. Dory6011



(e) New2 vs. Dory6011



(b) New2 vs. Dory6412

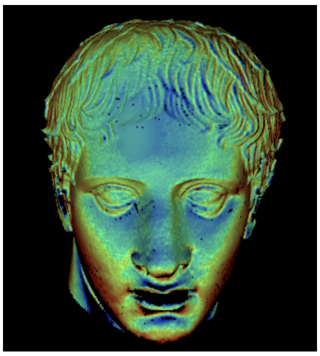


(f) New2 vs. Dory6412

(c) New2 vs. DoryM

(g) New2 vs. DoryM

(d) New2 vs. DoryPQ



(h) New2 vs. DoryPQ

Figure 4.3.3: New model 2 vs. others. New model combines herm DoryPQ and head of statue DoryM. (a)-(d) show the shape differences based on whole head alignment, while (e)-(h) are matching results where only the front parts are taken into account.

normalizing.

After normalizing all heads into same scale, we redo this pair-wise comparison. Results are shown in Table 4.3.3 and table 4.3.4:

Table 4.3.3: AD of Only Faces, with scaling (Unit: mm)

Face	**DoryPQ**	Dory6412	Dory6011	DoryM
DoryPQ	0	0.672	0.957	0.681
Dory6412	0.672	0	1.017	0.890
Dory6011	0.957	1.017	0	1.058
DoryM	0.681	0.890	1.058	0
Sum of AD	**2.310**	2.579	3.032	2.629

Comparison result shows that after scale normalization, the enlarged DoryPQ seems the best under the assumption of taking Doy6412's size as standard, by counting both whole head and just frontal face. Probably enlarged DoryPQ can serve as a standard model when comparing copies if the original size are able to be approximated.

Table 4.3.4: AD of Whole Heads, with scaling (Unit: mm)

Head	**DoryPQ**	Dory6412	Dory6011	DoryM
DoryPQ	0	0.783	1.133	0.841
Dory6412	0.783	0	1.251	1.014
Dory6011	1.133	1.251	0	1.323
DoryM	0.841	1.014	1.323	0
Sum of AD	**2.757**	3.048	3.707	3.178

5 Conclusion

In this section, we first summarize the contribution of this thesis and then discuss the temporary limitation as well as the possible future work.

5.1 Summary

Modern digital archiving technique provides a novel and reliable assistance to modern archaeology researches. As one 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 thesis, we proposed an intuitive 3D shape comparison procedure and apply it on the real Roman times sculpture data. We showed the framework of shape analysis of 3D sculpture models by detecting the local shape differences as an indicator to explore mysteries in Roman copies of classical sculptures. This framework consists of mainly three steps: model construction, alignment and difference visualization. After having three dimensional models, a *Region of Interest Guided Alignment* is introduced so that it becomes possible to emphasize the key part. Distances of point pairs between two models are calculated as indicator of shape difference and moreover, those are colour-coded to present the intuitive difference distribution. In addition, statistical evaluation of those point to point distance is introduced to achieve numerical similarity assessment.

The proposed method successfully verifies archaeological assumptions and provides a new perspective to heritage protection and research.

5.2 Temporary Limitation and Future Work

The 3D shape comparison framework proposed in this thesis successfully quantizes the comparison of classical sculptures and helps archaeological research with sound evidences. However there still exist several limitations in current method. For instance:

1. Manual interference still matters in the current comparison. In ROI-guided alignment, interest parts are selected manually and are affecting the finial results, though slightly. Therefore, an automatic segmentation, especially based on functional region will be very exciting.

2. In this thesis, only rigid alignment is utilised for the specific condition that only similar sculpture are studied. For more general application, it should be a good idea to introduce non-rigid correspondence/alignment, for some dissimilar comparison instances, so that the effect brought by different poses are excluded.

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