A novel method for the virtual restoration of cultural relics based on a 3D fine model

UN NOVEDOSO MÉTODO PARA LA RESTAURACIÓN VIRTUAL DE RELIQUIAS CULTURALES BASADO EN UN MODELO 3D FINO

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Miaole Hou[1,2], Su Yang[1], Yungang Hu[1], Yuhua Wu[3], Zhiquan Shu[2], and Xuedong Zhang[1,*]

[1] Beijing University of Civil Engineering and Architecture, Zhanlanguan Road 1#, Beijing, 100044, Beijing, China, zxd366@126.com, houmiaole@bucea.edu.cn

[2] University of Washington, WA 98115, Washington, U.S.A

[3] Historic Cultural Research Institute, Gaoyuan Street 2#, Beijing, 100029, Beijing, China

RESUMEN

- Las técnicas de rehabilitación Virtual son ampliamente utilizadas en la protección de reliquias culturales. Debido a la falta de las evidencias necesarias para la restauración virtual de reliquias culturales, en este documento se propone un método virtual 3D de restauración, que utiliza un modelo de regresión para estimar la restauración de un grupo de reliquias. Se establece un modelo de regresión predictiva a partir del análisis de las características geométricas de las partes intactas a fin de reflejar las relaciones de escala entre las características geométricas. A continuación, las características geométricas de las piezas incompletas o faltantes fueron predichas con el modelo de regresión propuesto. La precisión de la restauración virtual de las reliquias culturales puede ser mejorada significativamente con este método. Por último, se utiliza como ejemplo la restauración de los dedos que faltan de la estatua Dazu Thousand-Hand Bodhisattva. Para probar el método, se escogió la longitud inexacta de un dedo medio existente (que era de 216 mm). La posible longitud real del dedo medio se calcula con el modelo de regresión (que era de 235 mm con un error de predicción de ±7 mm). La prueba mostró el método propuesto es factible para restauración virtual en un grupo de reliquias.
- **Keywords:** Restauración virtual, restauración de evidencias, características geométricas, modelo de regresión.

ABSTRACT

Virtual restoration technology is widely used in the protection of cultural relics. Due to the lack of restoration evidence needed for virtual restoration of cultural relics, a 3D virtual-restoration method is proposed in this paper which uses a regression model to estimate the restoration evidence of a group of cultural relics. A predictive regression model was established by analyzing the geometric characteristics of the intact parts of a group to reflect the scaling relations among the geometric characteristics, then the geometric characteristics of the incomplete/missing parts were predicted using the proposed regression model. The precision of the virtual restoration of cultural relics can be improved significantly with this method. Lastly, the restoration of incomplete/missing fingers of the DaZu Thousand-Hand Bodhisattva statue is used as an example. To test the method, the length of an existing defective middle finger (which was 216 mm) was chosen, and the possible actual length of the middle finger was successfully estimated with the regression model (which was 235 mm with a prediction error of ±7 mm). The test results showed the proposed method is feasible for virtual restoration in a group of relics.

Keywords: Virtual restoration, Restoration evidence, Geometrical characteristic, Regression model.

1. INTRODUCTION

A large number of precious cultural relics have been recovered in China. However, with the passing of time and the influence of human activity, these cultural relics have been destroyed to some degree [1]. In recent years, because of the rapid development of three-dimensional (3D) laser scanning technology and 3D reconstruction technology, 3D relic models for complicated geometric structures have been acquired more easily and the precision of the models has also been improved [2], which has provided important data for cultural relic virtual restoration [3, 4]. Furthermore, technical support has been provided by virtual-restoration technology for the protection of cultural relics, such as reducing the difficulty of actual operation, avoiding further damage to relics due to improper treatments, digital 3D exhibition of the relics, etc. The protection of cultural relics has been greatly improved by these techniques [5].

As a result of these advance, definite progress has been made in virtual restoration of cultural relic and other similar field. For example, N. Yastikli demonstrated the whole documentation process of historic buildings including data acquisition, data processing, and final product can be carried out in a digital environment with the help of the automated procedures and digital aids [6]. Q. Huang, et al. presented a method for automatic reassembly of fractured 3D solids, which assembled the broken object by using purely the geometric information contained in the fracture surfaces of the fragments [7]. L. Arbace, et al. designed some innovative methodologies and used them to restore the Madonna of Pietranico, a terracotta statue severely damaged in the 2009 earthquake [8]. H. Biermann, et al. proposed an algorithm based on multi-resolution subdivision surfaces, which could be successfully used for the texture repair of a 3D relic model [9]. Y. Yu, et al. introduced a mesh-editing approach based on the theory of Poisson equation, which could produce desirable results for both global and local editing operations, such as deformation, object merging, and smoothing [10]. X. Zhang, et al. presented a case study of 3D virtual reconstruction for the CT-acquisition-based study of a cultural heritage artifact [11]. A. Koutsoudis, et al. presented an idea of performing 3D shape matching of complete or nearly complete 3D vessels by encoding a pair of depthmap images using compact 2D shape descriptors [12]. A. Pescia, et al. described a approach aimed at studying the ancient part of Palazzo d'Accursio (Bologna, Italy) using the Laser scanning [13]. K. Ikeuchi, et al. developed a robust simultaneous registration method and an efficient and robust voxel-based integration method, and synthesized several buildings and statues using scanned data and literature survey with advice from experts [14]. X. Cheng, et al. introduced a real 3D digital method for Wen-Yuan Building(in Tongji University, Shanghai, China) using 3D laser scanner and total station [15]. M. Levoy, et al. described a system for digitizing the shape and color of large statues, and a demonstration of this system on the statues of Michelangelo [16]. However, The above methods mostly have been applied only to cases in which the fragments have been found and the damage boundaries are clear, or texture editing can be easily conducted, or specific application needed to produce innovative solutions and to demonstrate their effectiveness on the field, so that the same relic can be obtained different remediation results by different researchers when the precise original dimensions of the relics are unknown. Therefore, accurately restoring relics to their original features is still a challenge.

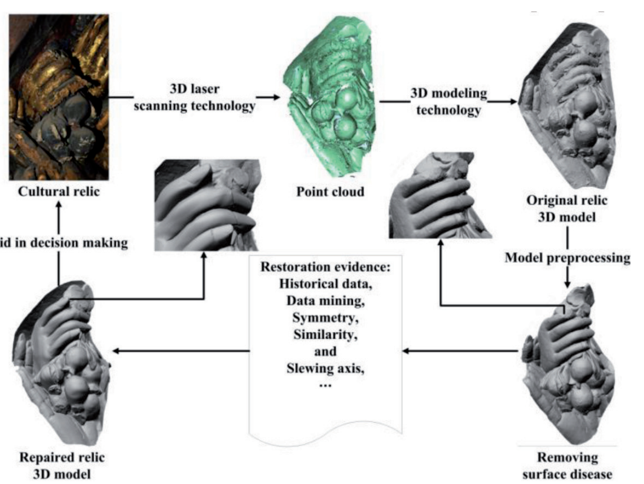

Fig. 1: Process of virtual restoration of relics based on 3D laser scanning

In order to address this problem, a novel method of cultural relic virtual restoration based on a 3D fine model is developed in this work, which makes up the insufficient of non uniqueness for the virtual restoration in the case of missing the damaged parts of cultural relic.The size information of the missing parts is predicted via the mathematical model which is fitted by known geometric characteristics of cultural relic, so that the virtual restoration of cultural relic is closer to the original features. According to the geometric characteristics of relics in a group, a predictive regression model is set up, and the geometric dimensions of the incomplete parts are then estimated. Then the estimated results are used as the restoration evidence in order to accurately restore the relics. The incomplete finger restoration of the DaZu Thousand-Hand Bodhisattva Statue is used as an example in this study. The results show that the method is feasible and effective for the virtual restoration of a group of relics.

2. RESEARCH METHODS

2.1. VIRTUAL RESTORATION

Finding the incomplete/missing parts of relics is the core issue in the process of cultural relic virtual restoration. Hence, virtual restoration should accurately give the original shapes and dimensions of relics. Therefore, the precision of restoration evidence, used as a measure of the virtual-restoration effect, is key. In order to identify the restoration evidence, historical data and symmetry and similarity of the relics are found using current methods. For example, a geometric method has been proposed to estimate the axis of a fragmented relic, restore its profile curve, and generate the profile around the axis of the original model [12]. A method has also been proposed for restoring original shapes using a group of similar objects and a matrix recovery [13]. However, these methods can not be applied to a group of relics, which are disorganized and have various shapes.

To address this problem, a 3D fine model of incomplete relics was reconstructed with 3D laser scanning technology. The process of cultural relic virtual restoration is shown in Fig.1. Regression analysis was used for estimating the geometric characteristics of the group of relics, then the regression model, which reflected the geometric characteristic of the relics, was set up. Finally, the incomplete relics were restored accurately according to objective restoration evidence. The point cloud data of the relics was acquired with a 3D laser scanner, and then 3D relic fine models were reconstructed with 3D reconstruction technology. On the basis of 3D relic fine models, the diseases on the surface of relics that affected simulation restoration, such as warped gold foil, weathering, and fractured rock mass, were removed during preprocessing of the model. The important geometric characteristics that can help depict the shapes of relics were analyzed. The correlativity of the geometric characteristics was set up using the regression model, so the estimation of the geometric characteristics of the incomplete parts was achieved according to the geometric characteristics of the intact parts of the group. Then the results of the regression model were used as the restoration evidence, and the incomplete parts of the relics were restored using surface fusion and surface reconstruction based on the restoration evidence. Finally, the 3D models of the relics were acquired, which were similar to the original shapes. The models can be used make restoration decisions such as 3D calculations, control points, plane, and section plans.

2.2. REGRESSION MODEL

Regression analysis is a mathematical tool used to model the correlation between an independent variable x and a dependent variable y. If there is only one independent variable in the model, it is called a simple regression model. The scaling relation is also reflected between the independent variable x and the dependent variable y in the model, so that the independent variable x and the dependent variable y can be used to estimate each other. The regression model is described as follows:

$$Y = \hat{a} + \hat{b}x \tag{1}$$

Where

$$\hat{a} = \frac{1}{n}\sum_{i=1}^{n} y_i - \frac{\hat{b}}{n}\sum_{i=1}^{n} x_i \ , \ \hat{b} = \frac{n\sum_{i=1}^{n} x_i y_i - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}$$

2.3. DATA PROCESSING METHOD

2.3.1. CENTERED LEVERAGE VALUE

The centered leverage value was the first parameter introduced in the test. Although those data points far away from average predictor values could be identified by this parameter, these points did not necessarily have a large effect on the result of the regression model. So this parameter could be used to detect the length of the ring finger and tell if it was abnormal, with standard hii<0.025.

$$ch_{ii} = \frac{(X_{i1} - X_1)^2}{SSX} \tag{2}$$

Where

$$SSX = \sum_{j=1}^{n} (X_{i1} - X_1)^2$$

2.3.2. STUDENT DELETED RESIDUAL

The student deleted residual is the quotient between the residual and its standard deviation. The student deleted residual is used to calculate the student residual excluding the ith data, and it reflects the impact of the ith data in the predicted value, which can judge whether y is abnormal with standard SREi< ±1.

$$SER_i = SRE\left(\frac{n-p-1}{n-p-2} - \frac{SRE_i^2}{n-p-2}\right)^{-\frac{1}{2}} \tag{3}$$

Where

$$SER_i = \frac{e_i}{MSE\sqrt{1-h_{ii}}}$$

Here, ei is the crude residual, MSE is the mean square error of the regression model, n is total amount of samples, and p is the number of fitted parameters in the model.

2.3.3. COOK'S DISTANCE

Cook's distance (D) is commonly used to estimate the influence of the data points to the least square regression analysis. Cook's distance can measure the effect of deleting a given observation. If data points have a large residual or high leverage, the regression model result could be incorrect. So in the regression analysis of the test, points were considered abnormal when Di<0.01.

$$D_i = \frac{e_i^2}{pMSE}\left[\frac{h_{ii}}{(1-h_{ii})^2}\right] \tag{4}$$

3. EXPERIMENT AREA AND DATA PROCESSING

3.1. EXPERIMENT AREA

In this paper, the Dazu Thousand-Hand Bodhisattva Statue (Fig.2.) was used as the experiment object. It is located in the country of Dazu in the city of Chongqing and is an important component of the Dazu Rock Carving. The most famous and

Fig. 2: Dazu Thousand-Hand Bodhisattva Statue. (a) Visible light photograph.(b) Orthorectification image based on 3D mode

distinctive symbol of the Dazu Thousand-Hand Bodhisattva Statue is that there are nearly 1000 Bodhisattva hands, which are in different shapes, possess all kinds of dharma instruments, and are distributed radially around the Bodhisattva. From a distance, the Dazu Thousand-Hand Bodhisattva Statue appears to be covered by gold foil, which presents magnificent depth, vivid patterns, and a resplendent landscape. However, upon closer observation, it is clear that the rock mass has been weathered and the gold foil has fallen off due to aging, and a large number of the Bodhisattva hands have been damaged to different degrees, which seriously affects the artistic value of the cultural relic. Therefore, it urgently needs to be protected and restored with scientific methods. Different shapes of the Bodhisattva hands embody different Buddhist meanings, elements of the Dazu Thousand-Hand Bodhisattva Statue that particularly fascinate archaeologists. However, archaeological activities have been limited due to the incomplete fingers in the Dazu Thousand-Hand Bodhisattva Statue. Therefore, restoring the shapes and dimensions of the Dazu Thousand-Hand Bodhisattva Statue to its original state is the primary task, to both the protect it and encourage archaeological research.

A 3D fine model of the Dazu Thousand-Hand Bodhisattva Statue was established based on a 3D laser scanner technique. By analyzing the 3D fine model, we know that the rock carving statue is 7.7 m high, 12.5 m wide, and has 829 Bodhisattva hands and arms in total. In order to differentiate the hands, the Dazu Thousand-Hand Bodhisattva Statue was virtually divided into 99 (9*11) small rectangle areas, and an ID was assigned to each hand.

3.2. DATA PROCESSING

In order to estimate the length of the incomplete fingers in the Dazu Thousand-Hand Bodhisattva Statue, two groups of data, where the middle finger and the ring finger were intact in the same hand, were used for the experiment. One group includes the lengths of the ring fingers and the middle fingers of 88 hands as the experimental data, which were used for setting up a regression model; the other was the lengths of fingers in 20 hands used as the verification data, in order to verify the regression model.

For the purpose of finding the abnormal data in the process of data preprocessing, the first regression model was set up according to the experiment data, and the abnormal data were analyzed using new model. After the abnormal data were removed, a second regression model was set up, which was used as the final result for the prediction of finger lengths, and the lengths of incomplete fingers were estimated as the restoration evidence. Because the scaling relation was reflected by the model between the middle finger and the ring finger in the same hand, if only one middle finger or one ring finger was intact in the same hand, the length of the other incomplete finger could be estimated according to the second model. Furthermore, a prediction error interval was given for adjusting the length in construction. Finally, the regression model was verified using the verification data, which assured the reliability of the restoration evidence. The data processing workflow is shown in Fig.3.

3.3. HYPOTHESIS TESTING

The primary purpose of the data preprocessing was to judge whether a linear relation existed in the observed data, which was the precondition of our method. The result of the experiment is shown in Figure 4, which confirmed the linear relation between the middle finger and the ring finger in the Bodhisattva hands. Therefore, it was reasonable to predict the data with a simple linear regression model.

The second purpose of the data preprocessing was to remove the abnormal points from the experiment data, to ensure the precision of the restoration evidence. Although some abnormal data could be identified visually, such as the point in the red box in Fig.4., we could not find all the abnormal data in this way. Therefore, the use of a statistical method for abnormal-point recognition was used to make the research more scientific and objective. Statistically speaking, the regression model could describe the scaling relation among the fingers, but this method, based on the least-square principle, was very sensitive to abnormal data. A small number of abnormal points could lead to a regression model with a relatively large number of errors. Therefore, in order to get a reliable regression model for accurately estimating the lengths of fingers, the abnormal data had to be removed. From a historical relic point of view, archaeologists are concerned not only with the relic as a whole, but also with the abnormal points in the Bodhisattva hands. In the Dazu Thousand-Hand Bodhisattva Statue, these abnormal points were caused by factors such as the original form of the

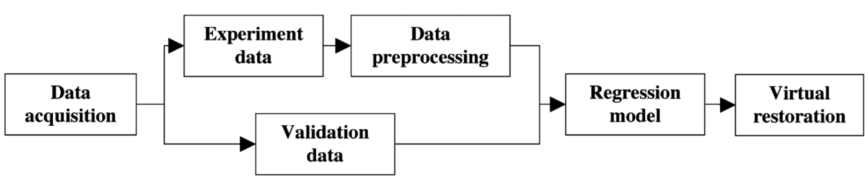

Fig. 3: Data processing workflow

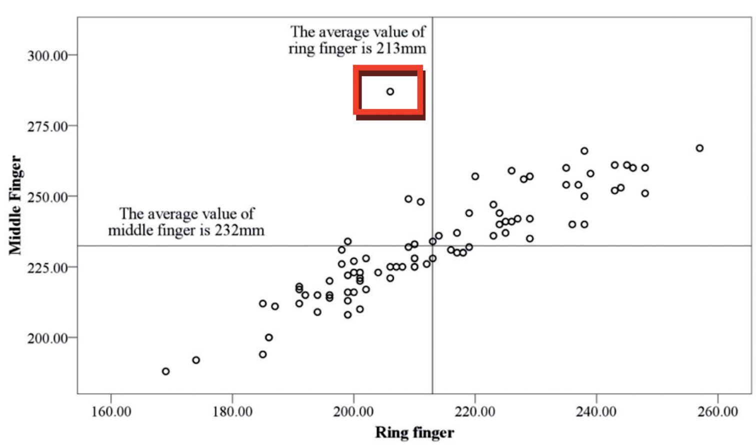

Fig. 4: Scatter diagram of experiment data

rocks, special carving skills, coordinate systems of the relics, or other unknown reasons. Spatial analysis of these abnormal points could provide new archaeological information. Therefore, extracting abnormal points not only improved the precision of the regression model, but also provided clues for archaeologists.

4. RESULT ANALYSIS

4.1. ABNORMAL-POINT ANALYSIS

The results of abnormal-point analysis according to the centered leverage value, the student deleted residual, and Cook's D, are shown in Fig.5. As can be seen in Fig.5., when Cook's D was normal, the centered leverage value or the student deleted residual was fairly large, and it was known that the lengths of the middle finger and ring finger were abnormal, but the ratio between the fingers still matched the linear regression model. This shows that the hand types of the Bodhisattva these points represent are small or large, because these data did not have much of an impact on the regression model, and therefore, were not removed as abnormal points. But when Cook's D was very large, these data were removed as abnormal points. Because this small piece of data is not consistent with the length ratio of the vast majority of the middle finger and ring finger, So, we do not hope to reduce the prediction accuracy of the regression model caused by a small part of abnormal data, even make the regression model meaningless because of large prediction interval.

4.2. REGRESSION MODEL

After the data preprocessing, 22 groups of data were removed in the second regression analysis. The fitting of straight-lines and the distribution of 66 groups of data pre- and post-processing are shown in Fig.6.(a). The dotted line shows the result of data preprocessing, which verified the simple linear relation among different fingers. The solid line shows the results of the second regression analysis, which was set up after data preprocessing. The final regression equation is as follows:

$$y=0.828x+54.819 \quad (5)$$

where y is the length of the middle finger and x is the length of the ring finger (in mm).

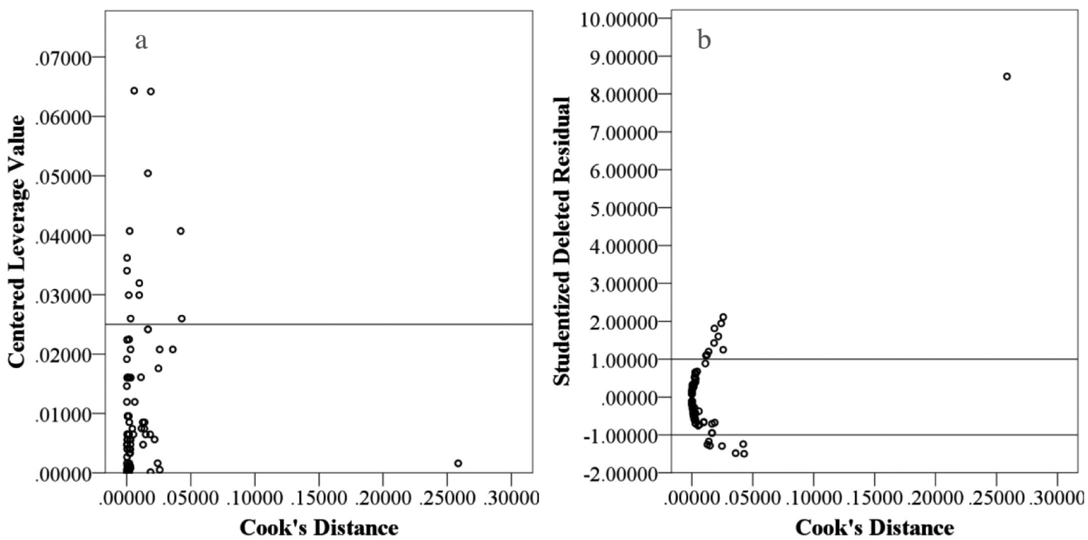

Fig. 5: Results of the three parameters: (a) Centered leverage value; (b) Student deleted residual

Hand ID	Measure value /mm	Prediction value /mm	Error /mm	Hand ID	Measure value /mm	Prediction value /mm	Error /mm
2-3-S1	234	230	4	4-9-S15	229	226	3
2-3-S2	222	225	-3	4-9-S12	227	230	-3
2-9-S3	227	230	-3	5-1-S6	234	229	5
2-9-S1	217	227	-10	5-7-S3	221	221	0
3-11-S2	228	224	4	5-7-S2	240	242	-2
3-10-S5	237	234	3	5-9-S9	234	234	0
3-5-S5	233	234	-1	6-5-S3	238	237	1
3-1-S5	225	227	-2	6-11-S6	227	230	-3
4-1-S5	222	225	-3	6-10-S11	209	217	-8
4-9-S16	224	225	-1	6-10-S10	225	228	-3

Table 1 Measured and predicted length values of the middle fingers

In this linear regression model, the coefficient of determination (R^2) reflected the degree of approximation between the approximated regression line and the real data points. From Equation (6), we knew the coefficient of determination (R^2) was between 0 and 1. The closer to 1 the R^2 values were, the more accurate was the data fitting by the regression line.

$$R^2 = \frac{SSR}{SST} = \frac{\sum_{i=1}^{n}(\hat{y}_i - y)^2}{\sum_{i=1}^{n}(y_i - y)^2} \tag{6}$$

In this group of data, R^2 was 0.993, which proved the reliability of the equation in statistics. The normal distribution of the residual in the linear regression model is shown in Fig.6.(b), where two times the standard error is used as the estimation of the prediction interval, $2\hat{\sigma} = 7.0$ mm.

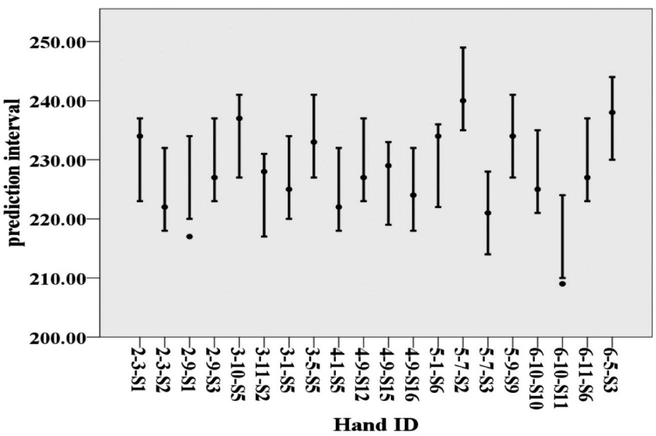

Fig. 6: Results of linear regression model. (a) Fitting straight lines and the distribution of 66 groups of data.(b) Normal distribution of the residual in linear regression model

4.3. DATA VALIDATION

In order to verify the regression model, Equation (5) was verified with 20 hands used as a set of validation data (Table 1). As shown in Fig.7., 18 of the 20 hands were in the prediction interval, while the other two hands (IDs:2-9-S1 and 6-10-S11) had the residuals of finger length 1 mm and 3 mm beyond the prediction interval, respectively.

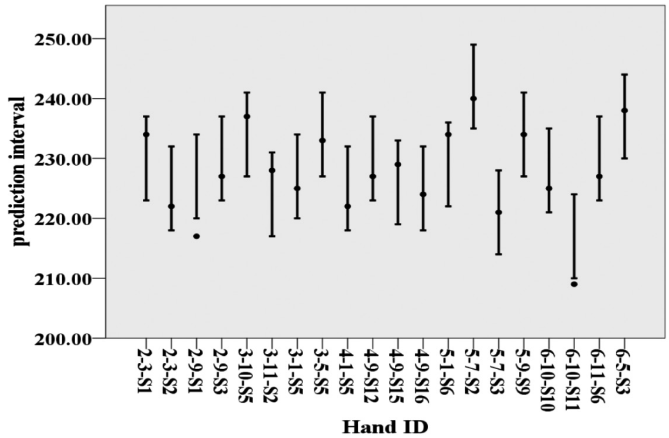

Fig. 7: Results of prediction interval

4.4. VIRTUAL RESTORATION

According to the regression model, the length of the ring finger in the hand ID: 8-9-S7 was 218 mm. The length of the middle finger, which was incomplete because of the weathering, was 216 mm. In order to calculate the length of the incomplete part, Equation (5) was applied to estimate the value. The prediction result was 235±7 mm. Therefore, the incomplete finger would need to be increased by approximately 19 mm. The error interval ±7 mm was used to adjust the finger length. The virtual restoration result of 8-9-S7 is shown in Fig.7..

5. CONCLUSION

In this work, a novel method of cultural relic virtual restoration based on a 3D fine model was proposed, which could improve the precision of relic restoration, especially for cases lacking restoration evidence. In the process of virtual restoration, a regression model for analyzing the geometrical characteristics of the group of relics was set up. Then the restoration evidence was ascertained using the regression model, which

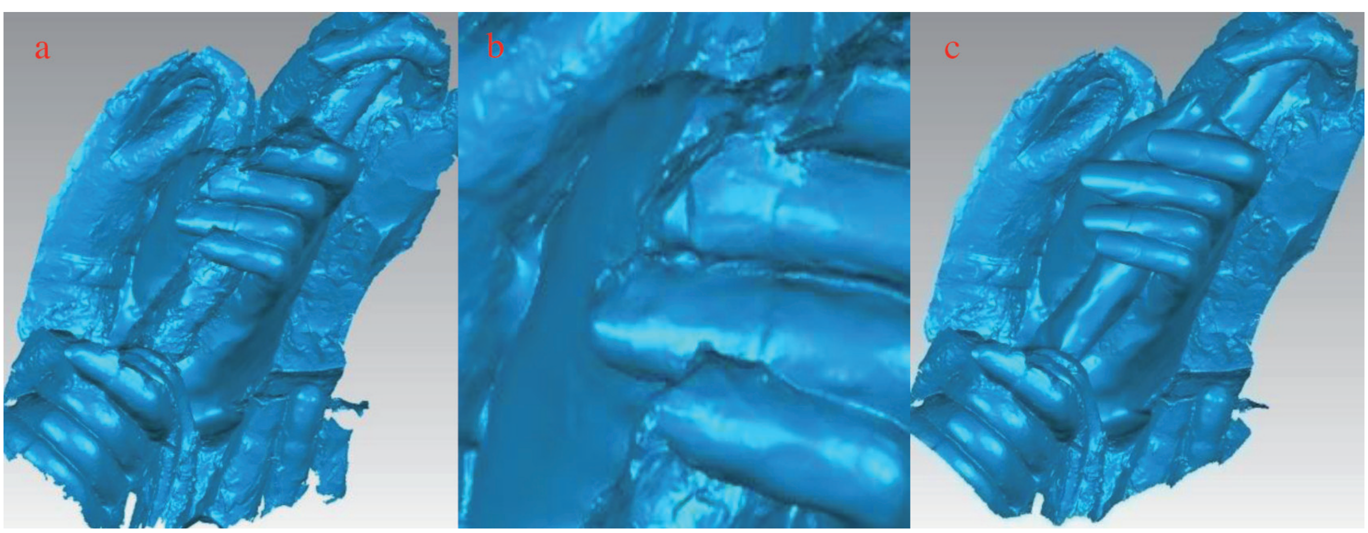

Fig. 8: ID 8-9-S7 Virtual restoration effect. (a) Original model.(b) Fractionated gain of the fingers. (c) Virtual restoration effect

could ensure the scientificity and objectivity of the relic restoration. The finger restoration of the DaZu Thousand-Hand Bodhisattva Statue was used as an example in the paper. The length of an incomplete finger was estimated by a predictive regression model. The computed result of the finger was 235 mm with a prediction error interval of ±7 mm. The results showed not only that the method is feasible for virtual restoration in group relics, but also may be useful for cultural heritage protection projects.

Although this method can provide the reliable size information of the missing parts of cultural relics when certain geometric characteristics exists linear relationship in the group of relics or similar cultural relics (such as Madonna, Bodhisattva, and Buddha), the size information and geometry information of missing parts often needed to be provided together when repairing severely damaged relics. Therefore, the next step is to mine more geometry information in the three-dimensional model of cultural relics to provide more reliable reference for the virtual restoration of cultural relics.

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