DE GRUYTER

AUTEX Research Journal, Vol. 24, No. 1, 2024, 20230047, DOI 10.1515/aut-2023-0047

BRINGING THE QUEEN MOTHER OF THE WEST TO LIFE: DIGITAL RECONSTRUCTION AND ANALYSIS OF TAOIST CELESTIAL BEINGS WORSHIPING MURAL'S APPAREL

Xiaotian Wang[1], Bingrong Huo[2], Xuyang Yuan[1], Zhiwen Lu[1,3], Feng Liu[1,*], Shengbin Zhou[1], Qiaoling Wang[1], Pengpeng Hu[4]

1 College of Textile Engineering, Taiyuan University of Technology, Jinzhong, 030600, China
2 Department of Architecture and Environmental Engineering, Taiyuan University, Taiyuan, 030032, China
3 Anhui Tianzhu Textile Science Technology Co., Ltd. Fuyang, 236000, China
4 Centre for Computational Science and Mathematical Modelling, Coventry University, Coventry, CV1 5FB, United Kingdom
*Corresponding author. E-mail: liufeng@tyut.edu.cn

Abstract:

Painted during the Yuan Dynasty, Taoist Celestial Beings Worshiping is a Taoist propaganda painting. It is one of the largest surviving ancient murals worldwide, featuring a variety of images of these beings dressed in costumes that vividly illustrate the blend of religious and artistic values in Chinese culture. To record and present the mural more intuitively and improve the study of Taoist Celestial Beings Worshiping, this article takes the example of five goddesses centered Queen Mother of the West in the mural and analyzes the styles, structures, colors, and patterns of the costumes from the perspective of costume engineering. Human models are established and the costumes at multiple levels are reconstruction by means of 3D virtual simulation technology. The display images are accompanied by QR codes, which can be scanned to view the 3D model. Finally, the Fuzzy Analytic Hierarchy Process was used to comprehensively evaluate the reconstruction effect of clothing, and the result was "good." The resulting digital figure can realize the "revitalization of cultural relics" and provides a new perspective for the digital exhibition of murals, which is conducive to the development of digital tourism and promotes the development of traditional culture.

Keywords:

Taoist mural painting, digital reconstruction, goddess costumes

1. Introduction

A mural is a form of painting that is done on a wall, which is one of the oldest forms of painting in existence. The ancient Chinese mural art dates back to the Han and Jin dynasties, and it flourished in the Tang and Song dynasties. Today, a significant number of famous Buddhist and Taoist murals have been preserved, which serve as evidence of ancient civilization and hold significant research and tourism value.

As science and technology have rapidly progressed, the protection of cultural relics has also entered the digital era. The concept of "Digital Dunhuang" was introduced in the 1980s and was completed in 2011. Since then, it has continued to evolve and has enabled the digital preservation and presentation of murals in their original state. With the advancement of 3D digital technology in recent years, it is now possible to transform realistic two-dimensional images into virtual three-dimensional models, providing a means to recreate the world of ancient frescoes.

Shanxi was renowned for its Buddhist and Taoist activities in the Central Plains region of China. Consequently, the region boasts an abundance of flourishing religious buildings, such as Buddhist temples and Taoist palaces. These sites are home to an impressive collection of frescoes, each of which possesses a unique history and artistic excellence that is unparalleled in China.

Among these remarkable structures is Yongle Palace, located in Ruicheng, Shanxi. It is the largest and best-preserved Taoist palace in China and is considered one of the world's largest remaining treasures of ancient fresco art. This distinction was acknowledged when it was added to the World Heritage Tentative List in 1998.

A significant type of Chinese wall painting is the monastery wall painting, which gradually developed with the emergence of Taoism and the introduction of Buddhism. One of the most exceptional examples of this art form is Taoist Celestial Beings Worshiping, a temple wall painting located in the Sanqing Hall of Yongle Palace. This exquisite piece was created during the Yuan Dynasty and depicts the story of the celestials worshiping the Primeval Lord of Heaven. The painting features various vividly depicted celestial beings, each depicted with striking colors and conveying a religious, artistic, and storytelling quality that makes it a masterpiece of Taoist murals. The mural on its west wall is shown in Figure 1.

The mural titled "In Worshiping" consists of around 290 characters and features a total of eight main figures, including six emperors and two queens, all standing at a height of 3 m. The remaining characters are arranged symmetrically in a ceremonial fashion. The characters are adorned in gorgeous costumes with coordinated colors, and their flowing clothes add to the grandeur of the mural.

Figure 1. *Taoist Celestial Beings Worshiping* Western Wall Murals.

Previous studies in *Worshiping* had emphasized mural art [1], religious significance [2], and other aspects, which only provide simple superficial descriptions of the costumes in the paintings. Specifically, the research on the costumes of *Worshiping* is in its infancy and is not systematic and comprehensive enough. Geng [3] researched and statistically classified the crowns of the 290 immortals in *Worshiping* and analyzed their relationship in the genealogy of Taoist immortals. Du [4] conducted a more detailed study on the styles, patterns, and colors of the female characters' clothing in *Worshiping*. Shangguan [5] analyzed the Taoist clothing elements in the mural costumes of Yongle Palace.

As characters play a significant role in the mural, they serve as the focal point for the study of 3D virtual reconstruction of mural paintings. Through the use of virtual simulation technology, we analyze the style, structure, and patterns of characters' costumes from a costume engineering perspective, which allows us to reconstruct three-dimensional digital virtual characters that can be animated and displayed in a variety of ways, thus achieving "cultural relics revitalization."

Moreover, the Yongle Palace is an important educational center, and the study and 3D virtual display of the mural's costumes contribute to the transmission and dissemination of traditional Chinese culture.

The images of the Six Emperors and Two Queens in Yongle Palace are the tradition of Tang and Song Taoist paintings, and the figures of the deities are outstanding in their temperament [6]. Among them, the Queen Mother of the West (henceforth, Western Mother), one of the eight main deities, plays a significant role in Taoist rituals. Additionally, her costume, with its atmospheric style and vivid colors, is typical and representative of *Worshiping*. Therefore, these five women, which comprise the Western Queen Mother in the Western Wall of *Worshiping* and the four female celestials beside her, are chosen as the research objects. Their characters and costumes are studied, analyzed, and virtually reconstructed.

The main contributions of this study can be summarized as follows:

1. It is the first study, to our best knowledge, to perform a 3D virtual reconstruction of the characters and costumes in the famous Chinese Taoist mural Worshiping.
2. A complete pipeline is proposed to reconstruct characters in murals. The semantic analysis of clothing for the five goddesses can be used as a reference for the development of educational or cultural tourism programs of *Worshiping*.
3. An evaluation system was established based on the Fuzzy Analytic Hierarchy Process (FAHP) to evaluate the three-dimensional reconstruction effect of mural characters and costumes from multiple indicators.

2. Related work

2.1. Development of digital protection of murals

The ancient frescoes that have survived throughout history are not only testimonies of ancient civilization but also of research value in various fields such as culture, art, and history. Despite this, these are immovable cultural relics and can be damaged by both natural and man-made causes, making it hard to deeply observe and experience in person. The current conservation of frescoes is mainly reflected in two aspects. One is the conservation of physical entities of murals [7], including the treatment of mural diseases by physical and chemical means, etc., which may cause secondary damage to murals. Additionally, digital technology has been used to conserve murals [8].

Numerous nations have been starting digitalizing cultural heritage in recent times. At the end of the last century, the British Museum and the Louvre Museum in France began digitizing their collections. In 2011, Google launched the Art Project, which cooperated with museums around the world, using Google Street View technology to take pictures of museum interiors and historical paintings in the museums, which were then converted into ultra-high-resolution images for global Internet users to enjoy. To summarize, heritage revitalization has become a fundamental research priority to protect, preserve, and utilize historical and cultural heritage. In particular, data storage, virtual restoration [9], and virtual display of frescoes [10] are the primary methods of digital conservation of frescoes at present.

2.2. Protection status of Worshiping

In 2021, the Shanxi Museum restored the mural *Worshiping* using 3D printing technology, restored the colors using digital restoration technology, and presented them as animation during the exhibition. The next year, Shanxi Province launched two digital collections of Yongle Palace, which still presented the mural content in two-dimensional form. Additionally, previously published studies about the costumes of the gods and goddesses in *Worshiping* were limited to costume culture, religious culture [11], and costume aesthetics [12]. Despite these prior research studies by numerous scholars, the digital reconstruction of Worshiping had not been studied previously.

In short, the research and 3D virtual reconstruction of the Yongle Palace mural costumes have positive effects on the innovative design of both heritage exhibitions and digital collections.

2.3. 3D virtual display of paintings

3D virtual simulation technology of clothing was mainly used in pattern making [13], fashion style design [14], clothing interaction design [15], and functional clothing design [16]. Furthermore, it is frequently used for costume restoration and 3D virtual displays. Currently, scholars have realized the 3D restoration of costumes in some famous paintings, such as Tang Zhao ling frescoes [17], Tang Tomb Murals [18], Han Xizai Banquet Painting [19], Spring Outing Painting of Madam Guo [20], and DaoLian Painting [21].

However, these studies only had a 3D virtual display of the mural costumes, the reconstruction of the appearance of the figures was not involved in the construction of the human models. Moreover, simulated costumes were mostly single-layered for modeling convenience.

The three-dimensional digital reconstruction of fresco-like cultural relics proposed in this article differs from the previous digital conservation of the physical entities of frescoes. The appearance of mannequins is taken into consideration, as opposed to the virtual restoration of clothing in paintings that is done by other academics. Its ultimate purpose is to reconstruct a virtual world conveyed by frescoes and to enhance the three-dimensional virtual display and interaction of the story content and context presented by frescoes. For example, in the project of the dynamic digital scroll of “Thousand Miles of Rivers and Mountains 3.0,” a 3D engine technology with real-time layered rendering has been used to create 3D models of the original painting’s mountains, buildings, and other elements, giving the audience an immersive and interactive experience.

3. Methods

3.1. General scheme

In this article, we selected Style3D virtual fitting software for 3D digital reconstruction of characters and clothing due to its simplicity and efficiency. Through Style3D, the structure of the fabric is able to be replicated digitally, resulting in a more realistic display of the characters and their respective costumes.

As a physical entity in two dimensions, the mural remains a digital two-dimensional model, even if the entire element is mapped to virtual space. However, the transition from a physical two-dimensional mural to a virtual one alone does not allow one to experience and perceive the world as it was imagined by the ancient people. Therefore, in the link between physical entities and digital models, it is necessary to include, in addition to technical aspects, the analysis of the 3D structure of elements in frescoes.

First, the semantic aspects of the costume are analyzed based on the mural images. Second, human body characteristics are estimated by consulting the literature and image measurement methods and a mannequin is built. Third, based on the previous analysis of clothing styles, colors, and patterns, a layer-by-layer virtual fitting from inside to outside is performed on the previously established mannequins to obtain clothing models. Finally, a virtual display system is built through QR codes.

The illustration of the proposed pipeline is shown in Figure 2.

3.2. Semantic analysis of the costume

Mark Western Mother as I with Roman numerals, and mark the four goddesses beside her as II to V in clockwise order (Figure 3a). The comparison shows that the costumes of the goddesses in the frescoes are similar. The clothing styles are large-sleeved robes, long skirts, etc., only the colors, patterns, and number of layers of clothing are different.

The semantic analysis is essential as it has a major influence on the results of the 3D virtual reconstruction in this study, with implications for planning education and tourism projects. The meaning of the costumes of these five goddesses is concerned with three aspects: the secular hierarchy, the era, and the religion.

First, the dress system of celestial beings in *Worshiping*, including the five goddesses, all inherited the secular dress system to a certain extent. From this, we can understand the layers and styles of their clothing. For example, the form of the dress of the Western Mother follows the dress system of the empress that dates back to the Qin and Han Dynasties [22]. She wears a pale ochre robe with large sleeves decorated with gold clouds and phoenix patterns on the edges, and a green square scarf with a turtle-back pattern on the cuffs; in the inner layer, she wears a stone-green pleated skirt; at the innermost layer, she wears a white Zhongdan (Chinese shirt, which was worn in the middle of a ceremonial robe or dress in ancient China) which can be seen from the cuffs and lower hem of the skirt; at the waist, she wears a vermillion knee covering and a large belt and ribbon hanging to the ground; in addition, she has a cape that wraps around her arms and drops over her knees. The other four goddesses also dressed up as aristocratic women in ancient China, with lower levels than empresses.

Second, the costume of these goddesses reflects the characteristics of traditional clothing from different eras in ancient

China. Their costume is part of the traditional clothing system of Han ethnic group, incorporating Mongolian characteristics because of historical background. For example, the adoption of the left lapel in the robes of Western Mother and Goddess V conforms to the habits of Mongolian people, which is usually the right lapel in Han people. And the reason is the influence of the Mongols who ruled China during the Yuan Dynasty. In China at the end of the thirteenth century, after the Yuan rulers had conquered the neighboring countries, various kinds of gold and silver jewelry and technical handicrafts were introduced from Persia and elsewhere. The Yuan, therefore, were fond of adding gold and inlaying treasures to their garments. The author of the mural used the gelled patterning and gilding painting techniques on the edge of large-sleeve robe of Western Mother, showing that it was a popular textile technology "Nashiya" in the Yuan Dynasty. Nashiya is the Persian phonetic translation, which refers to the weaving process with gold woven gold brocade [23]. In addition, the lower edge of the pleated skirt worn by Western Mother is decorated with a circle of pearls, which were favored by the Yuan rulers. Moreover, the skirt waist of Goddess III and Goddess IV is higher than those of the other three, which was located below the chest and prevalent during the Sui, Tang, and Five Dynasties.

Third, the costumes of the five goddesses reflect the ancients' imagination of Taoist immortals. This can be identified by the details of the costume, such as the halo on the head, the green feathers on the elbows of the sleeves, the red ribbons on the shoulders, the baby pattern on the right breast, and the pearls and jade ornaments on the collar and waist. In addition, Taoism holds the *I Ching* as its main ideology, and the center of the phoenix crown of Western Mother is decorated with the symbol of "Kun Gua," which implies the Taoist ideology of "Have Ample Virtue and Carry All Things." These details mainly come from the creation based on religious doctrine, which will be researched in the future study.

Based on the above analysis and combined with all 25 images of goddesses in *Worshiping* (Appendix 1), the following rules were summarized: (1) Their clothes wrapped around the waist have a fixed matching method, including ribbons, knee coverings, belts, and leather belts. (2) The color matching of their clothing is mainly based on the contrast between cold and warm. (3) Some styles of clothing have fixed color systems, such as white as the main color for ribbons and red as the knee covering. (4) Leather belts are usually arranged in square or circular shapes. Based on the above, we made artistic creations of styles and colors for the covered parts of the clothing concerning the visible clothing to enrich the display effect. For example, for Goddesses III and IV, some costumes of their lower bodies were invisible, so we added ribbons and set them to white. Other clothing is also designed with regard to the style and color rules we summarized above, of which the detailed steps will not be described.

In summary, we plotted the style diagrams of the main costumes of the five goddesses and extracted the colors and patterns from murals, as shown in Figure 3.

3.3. Body shape estimation under clothing

Although there are currently non-contact anthropometric methods for two-dimensional images [24], this method only applies to situations where the wearer's clothing is fitted. The clothing in the murals presents the characteristics of a large volume, so we use the method of manually locating feature points for anthropometry. However, the Western Mother is seated, and the postures of other goddesses are also various. So, part of their bodies is usually covered by each other in the painting. Therefore, we cannot measure the key dimensions of the human body through image measurement.

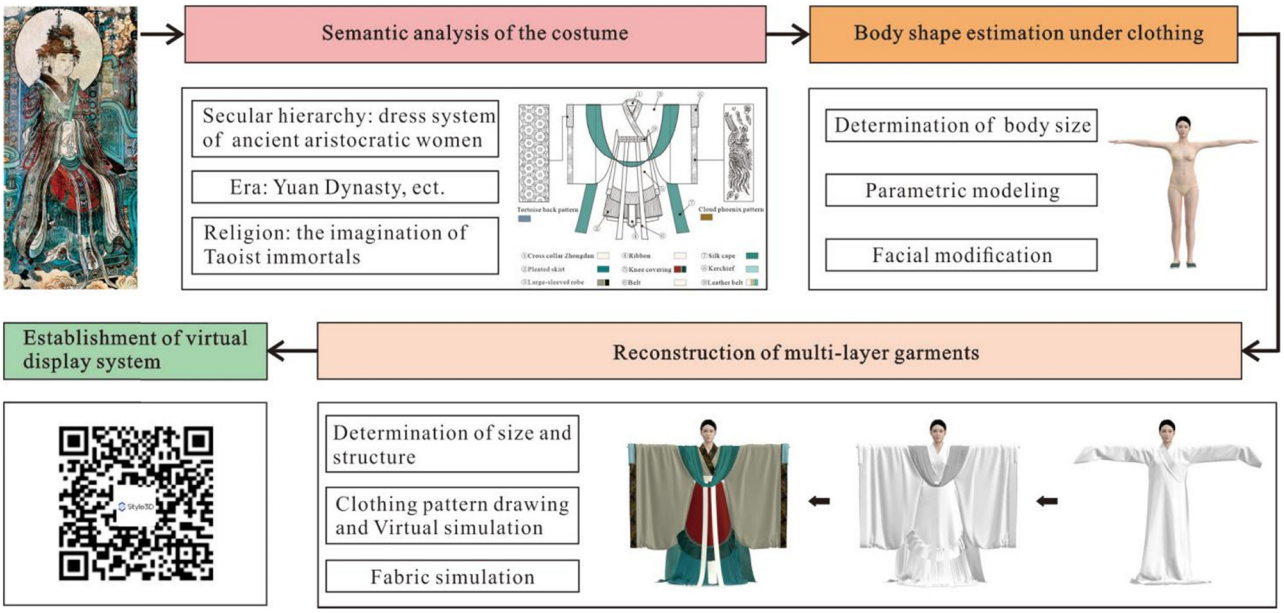


Figure 2. Illustration of the proposed pipeline.

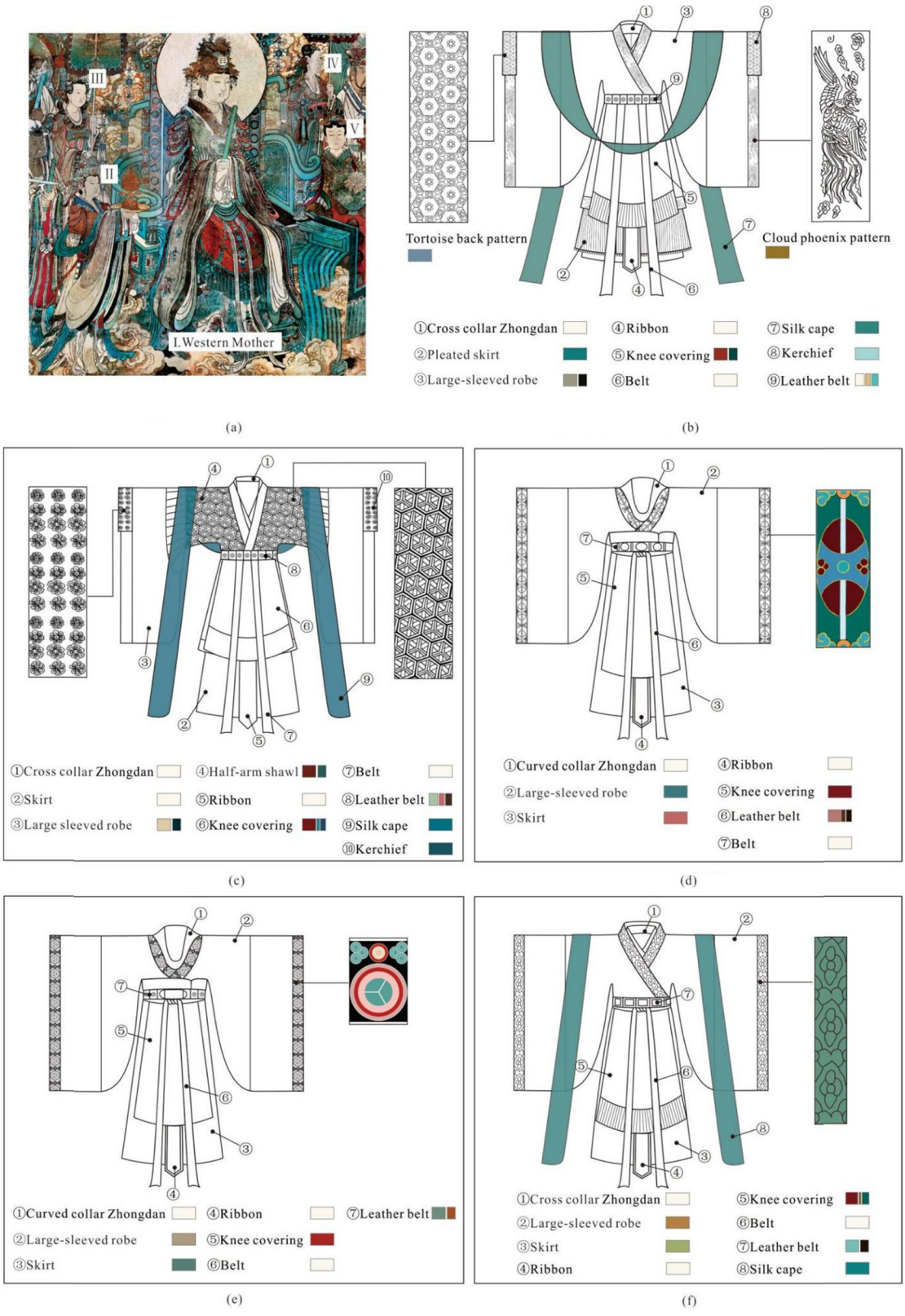


Figure 3. Semantic clothing analyses. (a) Mural image, (b) Goddess I. western mother, (c) Goddess II, (d) Goddess III, (e) Goddess IV, and (f) Goddess V.

However, the rules of human body shape in murals can be obtained by combining the results of image measurement. First, it can be known that the head–body ratio of the women with full-body portraits in *Worshiping* shows a distribution between 6.5 and 7.5 by measuring the pixel length of the character's head and body. It is in line with the basic Asian standard of proportion, suggesting that the mural is realistic. And then, Relevant data show that the average height of Chinese women in the Song Dynasty was 157.17 cm [25], which is close to the medium height of Chinese women. And

Table 1. Size of mannequin (unit: cm)

Code	Height	Bust	Waist	Arm span	Forearm length	CF neck to waist height	Head height	Waist height
Goddess I	165	88	67.84	168.34	27.10	33.41	22.64	104.70
Goddesses II–V	160	84	63.77	163.03	26.25	31.76	22.45	101.58

the corresponding standard clothing size for Chinese women is 160/84A. So, the height and chest circumference of the four goddesses next to Western Mother are set at 160 and 84 cm, respectively. However, the Western Mother is taller than the other immortals as the leader of the female immortals. So, the height of the mannequin of Western Mother is set to be 165 cm, and the bust is 88 cm. After entering the height and chest measurement into the software, the dimensions of other parts can be automatically adjusted in the software based on this. Some data will be given directly by the software, while other key data required for making clothing need to be measured on the three-dimensional model. The data are detailed in Table 1. For the data that need to be measured manually, the results given in the table are the average results of three measurements.

To make the 3D mannequin from the software resemble the goddess of *Worshiping*, an experienced artist was consulted to make the following adjustments to the 3D mannequin obtained from the software: the width of the face was increased, the width of the eyes was reduced, the mouth was raised, the eyelashes were hidden, the eyeliner was drawn, the eyebrows were thinned, and the skin tone was whitened (Figure 4).

3.4. Reconstruction of multi-layer garments

The human body model has been established, and the next step is to reconstruct the clothing models. We take the clothing modeling of Western Mother as an example to introduce the detailed steps of layer-by-layer modeling.

3.4.1. Determination of size and structure

The first step is to determine the clothing size and structure. The clothing size was determined by taking three factors into consideration. First, select the landmark pixel of the collar, waist, hem, and other parts of the garments manually, and then calculate the pixel length. As a result, the proportional relationship between clothing size and human body size, or the length of the clothing relative to the key parts of the human body can be determined. These are used to determine the garment size preliminarily. Second, because of the inability to measure the size of the covered part and folds of the garment, refer to the documents and the size of the unearthed cultural relic to set them. For reference of unearthed cultural relics, unearthed costumes from the Ming Dynasty are mostly chosen for the following reasons: first, the Ming Dynasty was the last feudal regime established by Han Chinese, and there are a large number of Han costumes among the unearthed clothing cultural relics and they are well preserved. Then, the Han costume originated in the Yellow Emperor period, matured in the Qin and Han Dynasties, and continued to the Ming Dynasty. The basic structural characteristics of Han costume have little changed until the Ming Dynasty [26]. Therefore, styles similar to the mural costumes can be found in the costumes unearthed in Ming Dynasty. Third, adjust the clothing size according to the actual situation during the experiment.

Only the upper part of the long-sleeved gown worn by Western Mother is visible, while the lower part is covered by other clothing. Referring to the large-sleeved gowns worn by other immortals in the murals, with slits on both sides, and the back body of the gown is longer than the front body, Western Mother should be of the same style. Therefore, using the robe unearthed from the tomb of Mrs. Wu, wife of King Ningjing in the Ming Dynasty, as a reference. The slits on both sides are close to the armpits, and the length of the front garment is 123 cm, and the length of the back garment is 145 cm. The latter is 22 cm longer than the former. Then, as seen from the mural picture, the hem of the front bodice of the gown with large sleeves is between the knee and the foot. Therefore, the

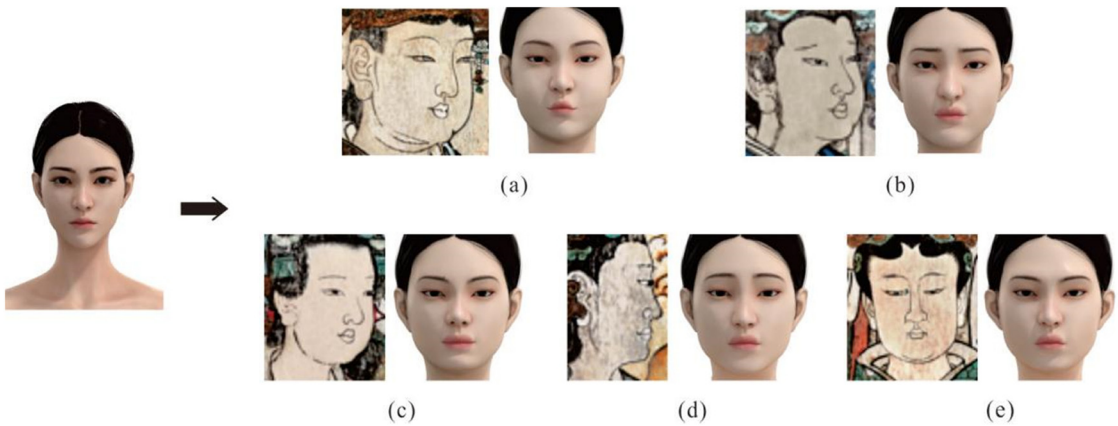


Figure 4. Facial modification of mannequins. (a) Goddess I. western mother, (b) Goddess II, (c) Goddess III, (d) Goddess IV, and (e) Goddess V.

height measured from the front neck point to the middle of the knee and the instep is 110 cm on the mannequin, which is used as the length of the front garment of the long-sleeved gown. Add 20 cm to the length of the back garment on this basis to be 130 cm.

According to the characteristics of traditional Han costumes, when the large-sleeved robe is used as a ceremonial dress, its sleeve length will cover the hands and can be folded back to the elbow. Therefore, the calculation formula is that the through sleeve length (the length between the two sleeves after the upper garment is laid flat) is equal to the length of the arm span plus twice the length of the forearm. From the data in the table, the length of the sleeve is calculated to be 222.54 cm (take 223 cm). The head height of the model is 22.64 cm, and the head height of the Western Mother in the murals is marked as the same height, and the ratio of head height to various parts is measured. Using this ratio, the fringe width is 5.97 cm (take 6 cm), and the 1/2 collar width is 10.91 cm (take 12 cm). Because the cuff is wavy, the cuff edge is divided into multiple straight lines when measuring the circumference, and the data are 219.91 cm (take 220 cm). Since the above measurement is a straight-line distance, but the garment is a curved surface, when setting the size, it should be added based on these data and rounded up for simplicity. Moreover, the large-sleeve gown is wide, so we take the hem width as 80 cm, anterior chest width (the distance between the left and right sleeve roots of the front garment) as 54 cm, and the sleeve root width (the length from the sleeve root to the shoulder line) as 35 cm.

The basic form of the clothing structure of the Chinese nation is a “cross-shaped flat structure,” characterized by “flat,” “integrated,” and “cross-shaped.” It takes the through sleeve length as the horizontal direction and the front and rear center line as the vertical direction. The large-sleeved robe worn by Western Mother is in the traditional Chinese cross-shaped structure, with a cross collar, left lapel, and wide cuffs.

A stone-blue pleated skirt is worn outside Zhongdan. Since the skirt is wrapped around the waist, the length of the skirt waist is 1.4 times the wearing waist, and it is set to 95 cm. The skirts of the same style in Worshiping just reach the ground, so we use the same length as the waist node height as the skirt length, which is 104.70 cm (take 105 cm). The structure of the skirt refers to the yellow silk pleated skirt that unearthed in Dingling, which is divided into two large pieces that are connected by the same waist head and overlap each other. To make the overlapping amount of the front and rear two skirts the same after the pleated skirt is closed, the calculation formula for the overlapping amount of the two skirts is: the overlapping amount is equal to the length of the waist minus the waist circumference of the human body, which is taken as 27 cm. Therefore, the length of the two skirts after pleating should reach 61 cm. The pleats of the pleated skirt are dense, so set the width of each exposed pleat to 1 cm and the width of overlap to 2 cm.

Only small parts of the cuffs and hem of cross collar Zhongdan are visible because it is in the inner layer. So, refer to the outer garment to determine its size. The collar width of Zhongdan is narrower than that of the large sleeve gown and is set to 20 cm. The sleeve length is slightly shorter than the large-sleeve shirt, so the sleeve length is set to 210 cm. The hem is slightly longer than the pleated skirt, and the length of the lower skirt is set to 120 cm. According to the above image measurement, the width of 1/2 cuff is 18.92 cm (take 19 cm). Moreover, Zhongdan is H-shaped, add 8 cm to the bust, and set the waist to 96 cm. Since the CF Neck-to-Waist height of the mannequin is 33.4 cm, the top length of Zhongdan is set to 40 cm.

According to the ancient literature on the structure of cross-collar Zhongdan, the upper garment and the lower garment are connected with each other. It is characterized by narrow sleeves, a narrow waist, and a wide hem. The upper part of the dress is structured in the traditional Chinese cross-shaped structure, and the lower part is made of six pieces of fabric that are each cut into two and twelve pieces in total. Twelve right-angle trapezoids are stitched together in a way that the right-angle edges are successively stitched together with oblique edges.

The size of the reconstructed main garment of Western Mother is shown in Table 2. According to the analysis in Figure 3, the results show the clothing styles of Goddesses II–V, and the size data and structure of each part of their clothing are available by the same method as above.

3.4.2. Clothing pattern drawing and virtual simulation

In the second step, we draw the garment pattern and perform garment virtual simulations on the established mannequin. According to the above analysis, the patterns of the main clothing of the five goddesses are shown in Figure 5.

Table 2. Reconstruction garment size (unit: cm)

Cloth	Measurements	Size
Large-sleeved robe	Length	Front 110
		Back 130
	Neck width	24
	Through sleeve length	223
	Cuff opening	110
	Hem width	80
	Anterior chest width	54
	Sleeve root width	35
Pleated skirt	Length	105
	Waist	95
	Hem around	366
Zhongdan	Length	160 (top 40, skirt 120)
	Neck width	20
	Through sleeve length	210
	Cuff	38
	Waist	96

The sequence number of each picture in Figure 3 represents the inside and outside sequence of clothing wearing, and ① is the innermost layer. We perform virtual simulation layer by layer in this order. The simulation of each garment follows the following process: First, arrange the garment pattern in the corresponding parts. Second, do the virtual sewing. Third, perform the virtual fitting, and flexibly use the selection move tool to adjust the shape of the garment. Finally, set the physical properties of the fabric to improve its realism.

We need to conduct virtual fitting in multiple layers and take Western Mother as an example to describe clothing modeling layer by layer. After simulating each garment, it was frozen to preserve its shape before simulating the outer garment. First, simulate the Zhongdan. Because it is a left lapel, when arranging the pattern, focus on arranging the right lapel on the outer layer of the left lapel. After the simulation is completed, freeze the Zhongdan, and arrange the pleated skirt on the outer layer of the Zhongdan for simulation. During the experiment, it was found that the inner and outer garment fabrics conflicted with each other and the simulation speed was slow, so the part that could be covered by the coat was deleted, leaving only the collar. Then, arrange the large sleeve robe on their outer layer to simulate. The outer layer of the big sleeve robe is ribbon.

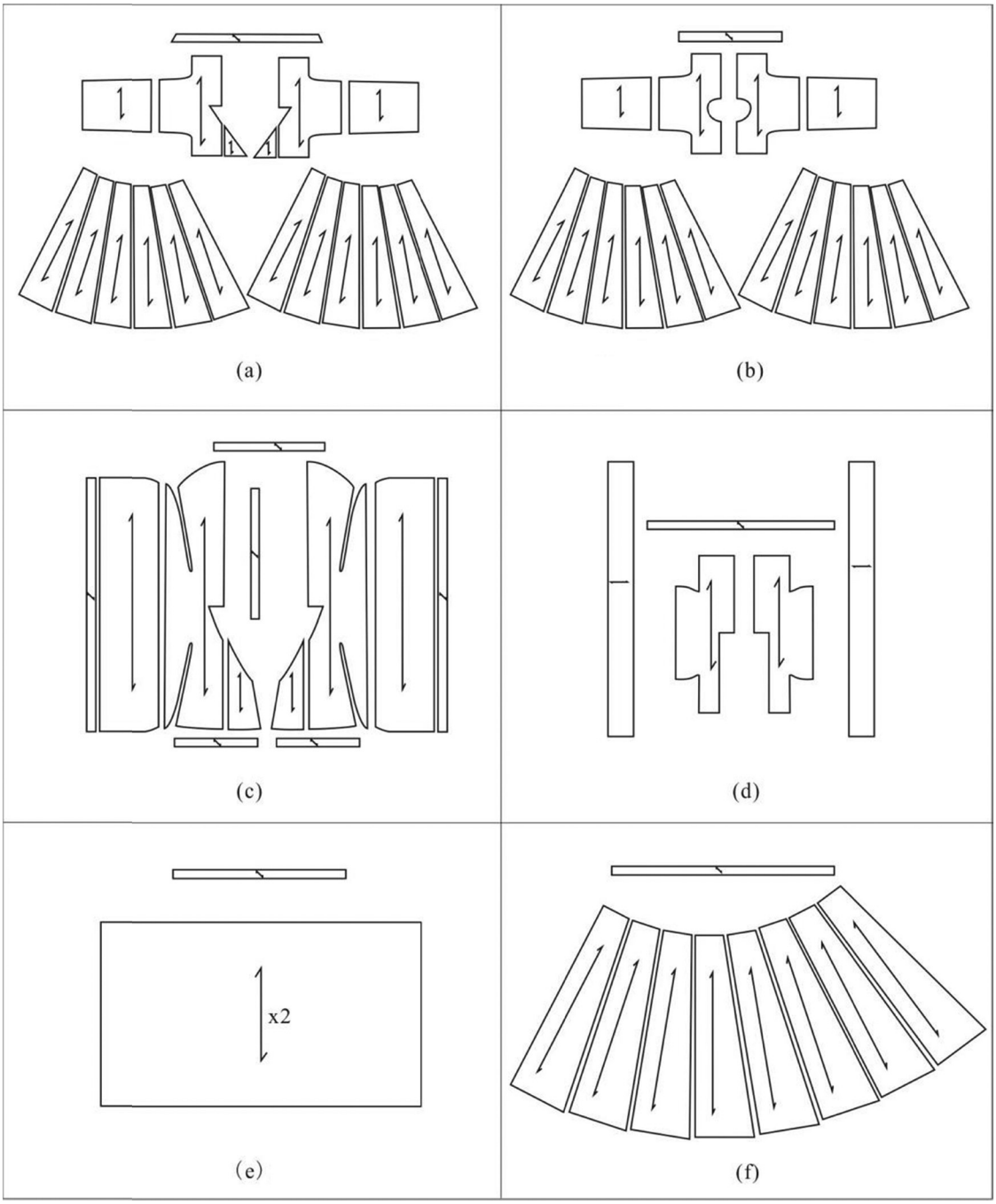


Figure 5. Main style garment patterns. (a) Cross collar Zhongdan, (b) curved collar Zhongdan, (c) large-sleeved robe, (d) half-arm shawl, (e) pleated skirt, and (f) skirt (Goddess II–V).

The ribbon hangs down to the ground, with the upper part being covered by the knee covering. In the outer layer of the knee covering, the belt is wrapped around the waist and hangs to the ground. We cut the belt into a belt and two straps that hang down and sew the hanging part to the belt. The silk cape cannot be arranged in a conventional way and needs to use the fixed pin tool to adjust its wearing form when the simulation is turned on. In addition, the silk cape is stacked on the shoulders. Therefore, add equidistant internal lines in the pattern and use the folded pleat tool to adjust the fold angle of each internal line. The layer-by-layer simulation steps are shown in Figure 6.

3.4.3. Fabric simulation

The third is to perform fabric simulation, which includes the setting of fabric properties, color, and patterns. The five goddesses are all dressed up as noble women, and the clothes they wear are made of noble silk fabrics. So, add silk normal mapping to all fabrics. There are a multitude of types of silk fabrics. According to the records of ancient documents, the common fabrics used in various clothing styles can be summarized. To express the material effect of the fabric, the physical properties that have a greater impact on the rendering effect – thickness and grammage – are selected as important indicators, and the parameters of different fabrics are set reasonably [27], as shown in Table 3. Additionally, to express the light and thinness of the silk cape, the transparency of the fabric is adjusted to 0.9.

The color of the fabric in Figure 3 is obtained by extracting the hue from the mural and adjusting the lightness and saturation according to the traditional Chinese color formula guide.

The clothing of five goddesses is patterned. Take Western Mother's big-sleeved gown as an example and the process of pattern generation in fabric simulation can be explained as follows. Based on the analysis of the patterns in Figure 3, for the cloud and phoenix patterns on the edges, a line sketch of the

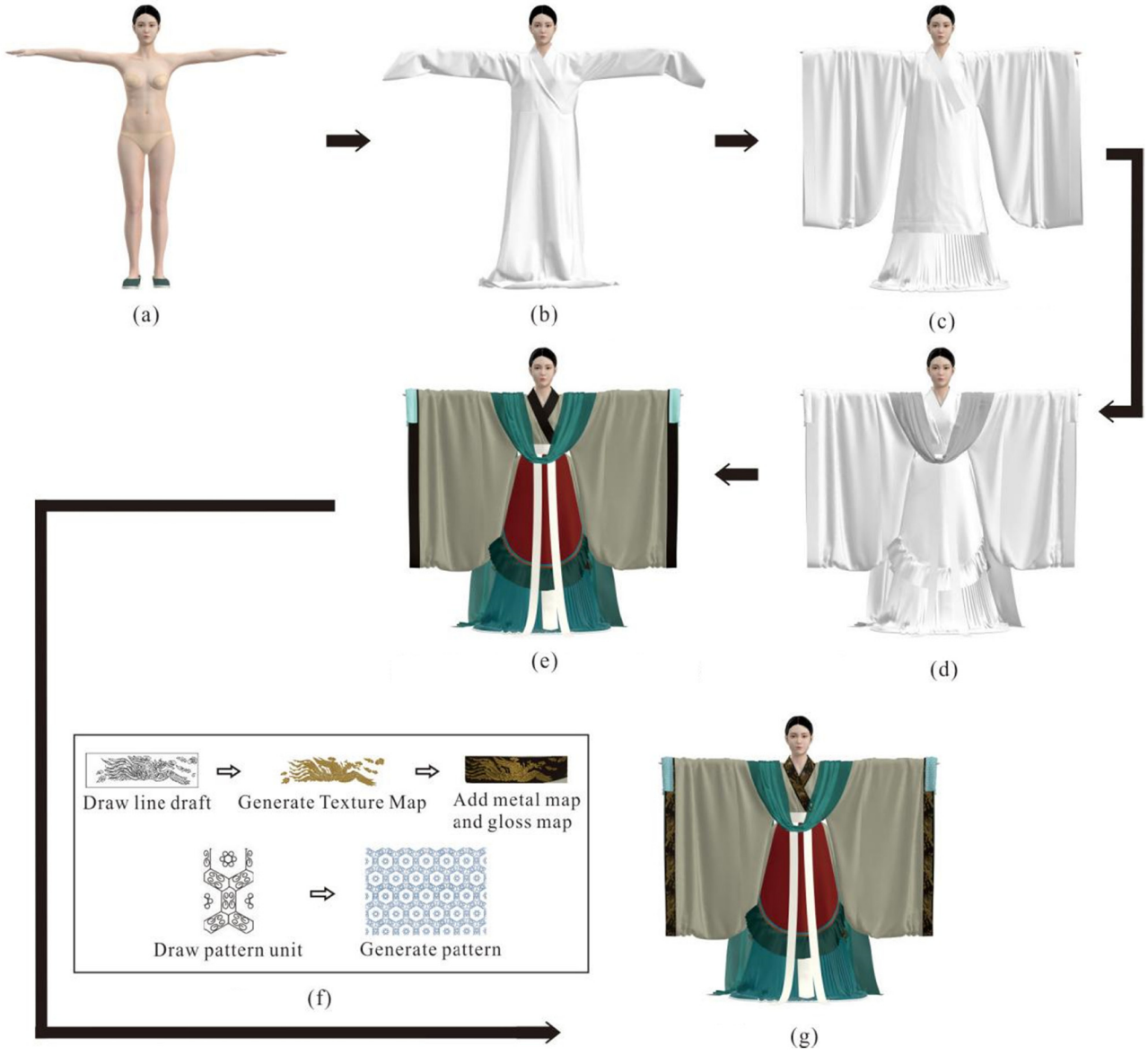


Figure 6. Overview of the garment reconstruction method. (a) Establish a mannequin, (b) simulate Zhongdan (c) simulate robe and skirt, (d) simulate all garment, (e) add colors and normal maps, (f) pattern generation, and (g) add patterns.

Table 3. Clothing material and physical property settings

Parameter	Zhongdan, knee-covering	Robe, skirt	Edge of the robe	Cape	Ribbon, belt
Texture	Gauze	Leno	Gilt brocade	Leno	Raw silk
Grams (g/m²)	65	100	129	43	71
Thickness (mm)	0.14	0.25	0.30	0.19	0.19

pattern is first drawn and then colored. After that, the texture maps are generated in the fabric generation system, and metal maps and gloss maps are added to show the effect of gold brocade; for the turtle-back pattern on kerchiefs embellished by the cuffs, draw the pattern unit first, then generate the four-sided continuous pattern in the fabric generation system. The pattern is generated as shown in Figure 6f. The final simulation effect is shown in Figure 6g.

3.5. Establishment of virtual display system

After building the model, a real-time virtual display system is established. The image is rendered in the software to obtain the front views of five goddesses after the virtual reconstruction is completed (Figure 7). Scan the QR code in the bottom right corner to view the 3D model and information on the official Style3D platform for the model of five goddesses.

Figure 7. Digital reconstruction effect. (a) Goddess I. western mother, (b) Goddess II, (c) Goddess III, (d) Goddess IV, and (e) Goddess V.

4. Establishment of evaluation system

We have reconstructed the costumes of the five goddesses in Worshiping, and the overall reconstruction effect needs to be evaluated next. When evaluating the effect of costume virtual restoration, various factors related to the costume are considered in determining the evaluation system. Therefore, the FAHP is used to evaluate the effect of this virtual reconstruction. The FAHP divides the factors that affect the evaluation objectives into several layers according to their attributes, and hierarchies of the problem. First, each indicator inside the tail layer is evaluated, and then a higher-level evaluation is performed layer by layer to obtain the evaluation results. The specific steps are as follows.

4.1. Structure of evaluation system

This evaluation considers detailed information such as model appearance, clothing style pattern, and so on. Establishing the evaluation system based on these factors, the analytic hierarchy process applies to divide the evaluation index system into a criterion layer and an indicator layer. The first layer represents the total target factor set $Z = (Z_1, Z_2, Z_3)$; the second layer represents the subtarget factor set $Z_1 = (Z_{11})$, $Z_2 = (Z_{21}, Z_{22}, Z_{23}, Z_{24})$, and $Z_3 = (Z_{31}, Z_{32}, Z_{33})$, to establish the evaluation system as shown in Table 4.

4.2. Determine the evaluation set of virtual reconstruction effect

The evaluation set is the set of evaluation results that evaluators can produce for each factor, and the evaluations of different evaluation indicators are different. A 5-point rating scale was used as the evaluation scale, $V = (v1, v2, v3, v4, v5)$ = (excellent, good, average, poor, very poor).

4.3. Determine the weights of each indicator

Different indicators have different impacts on the evaluation of virtual recovery effects, so it is essential to determine the weights of each indicator.

Table 4. Evaluation system of virtual reconstruction effect

Target layer	Criterion layer	Index layer
Reconstruction effect of virtual simulation Z	Model appearance Z_1	Make-up Z_{11}
	Garment silhouette Z_2	Zhongdan Z_{21}
		Large-sleeved robe Z_{22}
		Skirt Z_{23}
		Others Z_{24}
	Garment fabrics Z_3	Texture Z_{31}
		Color Z_{32}
		Pattern Z_{33}

First, the evaluation matrix G is established by inviting five experts to compare and rate each indicator using the 9-quartile scale method (Appendix 2), with G corresponding to $Z = (Z_1, Z_2, Z_3)$, $G1$ corresponding to $Z_1 = (Z_{11})$, $G2$ corresponding to $Z_2 = (Z_{21}, Z_{22}, Z_{23}, Z_{24})$, and $G3$ corresponding to $Z_3 = (Z_{31}, Z_{32}, Z_{33})$. Second, the hierarchical single ranking is conducted. The hierarchical single ranking refers to the ranking of the importance of each factor at the level for a factor at the previous level. The solution vector corresponding to the maximum eigenvalue of the judgment matrix, after normalization, is the ranking weight of the relative importance of the corresponding factors at the same level to a factor at the upper level. Third, perform consistency checks on the judgment matrix. If it passes the test, it proves to be valid, otherwise, the expert needs to repeat the comparison and recalculate the judgment matrix.

For example, the judgment matrix for primary indicators, based on the scores assigned by the first expert, is as follows:

$$G = \begin{bmatrix} 1 & 1/5 & 1/2 \\ 5 & 1 & 3 \\ 2 & 1/3 & 1 \end{bmatrix}. \quad (1)$$

The maximum eigenvalue and eigenvector of matrix G were calculated using Matlab, and the eigenvectors were normalized. The maximum eigenvalue $\lambda_{max} = 3.0037$ of the matrix G in equation (1) and the eigenvector normalized to w = (0.1220, 0.6483, 0.2297). These data represent the weight assigned by the first expert to the first level indicator, so the weight of the model appearance is 0.1220, the weight of the garment silhouette is 0.6483, and the weight of the garment fabrics is 0.2297.

To ensure coordination between the elements of the matrix G, the consistency index (CI) and consistency ratio (CR) are calculated by the following equations:

$$CI = \frac{\lambda_{max} - n}{n - 1}, \quad (2)$$

$$CR = CI/RI. \quad (3)$$

In equation (2), λ_{max} is the maximum eigenvalue of the judgment matrix and n is the order of the judgment matrix. In equation (3), the average random consistency index (RI) depends on the order of the matrix (n). When CR ≤ 0.1, the judgment matrix is considered having passed the consistency test. For matrix G in equation (1), CI = 0.00185 is calculated, and RI = 0.58 when n = 3 is known (Appendix 3), so the CR = CI/RI ≈ 0.0032 < 0.1, which passes the consistency test. Therefore, these data are valid.

The same method is used to obtain the weights assigned to each indicator by the other four experts. The weighting coefficients of primary indicators were obtained by synthesizing the weight vectors of the five experts by arithmetic averaging.

Similarly, the weight coefficients of the secondary indicators were obtained, and the comprehensive weight coefficients of each indicator were calculated, as shown in Table 5.

4.4. Establishment of single-factor fuzzy evaluation matrix

After determining the evaluation index weights, the evaluation data of the secondary indicators were summarized and counted

Table 5. Weight of reconstruction effect index

Primary index	Weighting	Secondary index	Weighting	Comprehensive weighting
Model appearance Z_1	0.1207	Make-up Z_{11}	0.1207	0.1207
Garment silhouette Z_2	0.5567	Zhongdan Z_{21}	0.0836	0.0465
		Large-sleeved robe Z_{22}	0.3490	0.1943
		Skirt Z_{23}	0.2694	0.1500
		Others Z_{24}	0.2980	0.1659
Garment fabrics Z_3	0.3226	Texture Z_{31}	0.1951	0.0629
		Color Z_{32}	0.4486	0.1447
		Pattern Z_{33}	0.3563	0.1149

by means of a questionnaire (Appendix 4). The respondents to the questionnaire were undergraduate students majoring in clothing-related fields. A total of 105 questionnaires were collected, of which 100 were valid, with a valid rate of 95.2%. The survey statistical results are shown in Table 6. According to the statistical results, the second-level single-factor fuzzy comprehensive evaluation matrix R was obtained.

4.5. Fuzzy comprehensive effect evaluation

Combining the weights of each indicator and the fuzzy comprehensive evaluation principle, the following formula was used to calculate the comprehensive evaluation value (B) of the virtual recovery effect.

$$B = AR. \quad (4)$$

In equation (4), A is the combined weight coefficient of each indicator, and R is the second-level single-factor fuzzy comprehensive evaluation matrix. B = (0.2386, 0.5761, 0.1801, 0.0051, 0) was calculated. The comprehensive evaluation results show that the affiliation degree of "excellent" is 0.2386, "good" is 0.5761, "average" is 0.1801, "poor" is 0.0051, and "very poor" is 0. According to the principle of maximum affiliation, the reconstruction effect is "good."

Worshiping is one of the most outstanding Chinese religious murals in terms of artistic achievement. In this article, a 3D digital reconstruction practice is conducted on the example of the five goddesses centered on the Western Mother of *Worshiping* in Yongle Palace. A user study was conducted using the FAHP, and the survey results showed that the reconstruction results were "good."

5. Conclusion and discussion

Both murals and traditional costumes are precious cultural heritages in the process of human civilization. In this study, based on costume digitization technology, we conducted a three-dimensional virtual reconstruction and display of the figures and costumes of five goddesses in *Taoist Celestial Beings Worshiping*, restoring the appearance of the characters and the style, color and pattern of the costumes. We came to the following conclusions and discussions:

1. The costumes of the five goddesses in *Worshiping* are included in the ancient aristocratic women costume system and reflect elements related to the Yuan and other dynasties and Taoism. 3D virtual display allows people to observe the image depicted in the mural from different angles, which is conducive to the inheritance of Chinese traditional culture.
2. The 3D virtual display of fresco figures and costumes has positive significance for both the conservation and dissemination of fresco-type cultural relics. It can facilitate the integration of cultural tourism projects and virtual reality, and has implications for the innovative design of digital collections.

Table 6. Score statistics of reconstruction effect

Criterion layer	Index layer	Excellent	Good	Average	Poor	Very poor
Model appearance Z_1	Make-up Z_{11}	0.21	0.47	0.32	0	0
Garment silhouette Z_2	Zhongdan Z_{21}	0.20	0.58	0.22	0	0
	Large-sleeved robe Z_{22}	0.18	0.47	0.33	0.02	0
	Skirt Z_{23}	0.42	0.55	0.03	0	0
	Others Z_{24}	0.20	0.68	0.12	0	0
Garment fabrics Z_3	Texture Z_{31}	0.15	0.57	0.26	0.02	0
	Color Z_{32}	0.25	0.73	0.02	0	0
	Pattern Z_{33}	0.24	0.56	0.20	0	0

3. The study of the structure of the costumes of the goddesses in the murals in this research provides a reference for their application in a variety of ways, such as games, animation, film, television dramas, and some related derivatives.
4. This article only reconstructs the main costumes and some accessories, the hair accessories, shoes, and other sophisticated accessories need to be further studied. In terms of model appearance, only the make-up is considered in this study, the hairstyle and posture are also important and need to be included in further studies. Besides, due to the limited operation space of the software, the face of the mannequin cannot reach high similarity with the original appearance of the mural figure, which requires further optimization.
5. Scene construction and interaction design are not considered in this study. During the formation of an educational or tourism project, creators can incorporate digital components to optimize the project. The virtual simulation software for costumes used in the article is only one option for 3D digital reconstruction of frescoes, and there are many more methods available. Besides the character reconstruction, the three-dimensional digital reconstruction of murals can also be further studied in three-dimensional scene construction, virtual reality interaction, and other aspects. With the upgrade of digital technology and the improvement of cultural research, the display and interaction of mural-type cultural relics will get further technical support and methodological innovation, which will add new forms for protecting cultural relics and the development of cultural tourism.

Funding information: This work was supported by the Research Project supported by the Shanxi Scholarship Council of China (2022-090), a Major decision-making consultation project of Shanxi Province Philosophy and Social Sciences Planning Project (2023YY051), and the Higher Education Reform Program by the Department of Education of Shanxi Province (J20230211).

Author contributions: Wang Xiaotian: Conceptualization, Validation, Formal analysis, Investigation, Software, 3D model, Writing – Original Draft; Huo Bingrong: Resources, Translation from Chinese to English, Writing – Review & Editing; Yuan Xuyang: Software, 3D models, Visualization; Lu Zhiwen: Methodology, Visualization, Writing – Review & Editing; Liu Feng: Supervision, Writing – Review & Editing, Project administration, Funding acquisition; Zhou Shengbin: Software, 3D models, Visualization; Wang Qiaoling: Software, 3D models, Visualization; Hu Pengpeng: Supervision, Writing – Review & Editing.

Conflict of interest: The authors state no conflict of interest.

Ethical approval: The conducted research is not related to either human or animal use.

Data availability statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

[1] Gao, B. (2015). Artistic features of dissertation Chaoyuan painting in Yongle Palace. Journal of Hunan University of Science and Technology (Social Science Edition), 18(04), 144–149. doi: 10.13582/j.cnki.1672-7835.2015.04.027.

[2] Ge, S. (2021). Study on the image of Queen Mother of the Western in Chaoyuan painting. Art Panorama, 09, 65–70. doi: 10.3969/j.issn.1002-2953.2021.09.012.

[3] Geng, J. (2006). A brief study on crowns of Chaoyuan painting characters in Sanqing hall of Yongle Palace. China Taoism, 06, 15–19. doi: 10.19420/j.cnki.10069593.2006.06.009.

[4] Du, Y. (2018). Study on the Female Characters costume in Chao Yuan Mural of the Yongle Palace. (Master dissertation). Taiyuan University of Technology, Jinzhong, China.

[5] Shangguan, W. (2021). Taoist costumes in the frescoes of Yongle Palace in Yuan Dynasty. China Religion, 02, 58–59.

[6] Zhao, W. (2021). Chao Yuan queue in the murals of Yongle Palace. Art Panorama, 12, 26–32. doi: 10.3969/j.issn.1002-2953.2021.12.003.

[7] Gu, W., Wei, Y., Liu, B., Hu, L., Zhong, L. and Chen, G. (2022). Polyacrylic acid-functionalized graphene@ Ca (OH) 2 nanocomposites for mural protection. ACS Omega, 7(14), 12424–12429. doi: 10.1021/acsomega.2c01364.

[8] Jiang, C., Jiang, Z. and Shi, D. (2022). Computer-aided virtual restoration of frescoes based on intelligent generation of line drawings. Mathematical Problems in Engineering, 2022, 9. doi: 10.1155/2022/9092765.

[9] Yang, J., Cao, J., Yang, H., Li, Y. and Wang, J. (2021). Digitally assisted preservation and restoration of a fragmented mural in a Tang Tomb. Sensing and Imaging, 22(1), 1–18. doi: 10.1007/s11220-021-00354-2.

[10] Xie, H. (2022). Digitized visual transformation of grotto art using deep learning and virtual reality technology. Scientific Programming, 2022, 10. doi: 10.1155/2022/5106036.

[11] Geng, J. (2006). A brief study of the characters' crown in Sanqing Hall of Yongle Palace Chao Yuan Painting. China Taoism, 6, 15–19. doi: 10.3969/j.issn.1006-9593.2006.06.007.

[12] Du, Y. (2016). Yuan fresco costume in Yongle Taoist Temple Chao Yuan Painting. Hundred Schools in Arts, 32(S1), 201–202. doi: 10.3969/j.issn.1003-9104. 2016.z1.069.

[13] Zhang, J., Innami, N., Kim, K. and Takatera, M. (2015). Upper garment 3D modeling for pattern making. International Journal of Clothing Science and Technology, 27(6), 852–869. doi: 10.1108/IJCST-01-2015-0003.

[14] Choi, K.-H. (2022). 3D dynamic fashion design development using digital technology and its potential in online platforms. Fashion and Textiles, 9(1), 9. doi: 10.1186/s40691-021-00286-1.

[15] Bao, C., Miao, Y., Gu, B., Liu, K. and Liu, Z. (2021). 3D interactive garment parametric pattern-making and linkage editing based on constrained contour lines. International Journal of Clothing Science and Technology, 33(5), 696–723. doi: 10.1108/IJCST-09-2020-0137.

[16] Hong, Y., Bruniaux, P., Zeng, X., Liu, K., Chen, Y. and Dong, M. (2017). Virtual reality-based collaborative design method for designing customized garment for disabled people with scoliosis. International Journal of Clothing

Science and Technology, 29(2), 226-237. doi: 10.1108/IJCST-07-2016-0077.

[17] Liu, X., Wang, R. and Xu, Q. (2022). Structure restoration of female costumes in Tang Zhaoling frescoes by 3D virtual fitting. Journal of Silk, 59(2), 87–93. doi: 10.3969/j.issn.1001-7003.2022.02.011.

[18] Liu, K., Wu, H., Ji, Y. and Zhu, C. (2022). Archaeology and restoration of costumes in tang tomb murals based on reverse engineering and human-computer interaction technology. Sustainability, 14(10), 6232. doi: 10.3390/su14106232.

[19] Liu, K., Wu, H., Gao, Y., Zhu, C., Ji, Y. and Lü, Z. (2022). Archaeology and virtual simulation restoration of costumes in the Han Xizai Banquet Painting. Autex Research Journal, 23(2), 238–252. doi: 10.2478/aut-2022-0001.

[20] Liu, K., Lu, S., Zhao, J., Jin, Z., Zhu, C., Zhu, K., Hao, X., Zhang, B., Lü, Z. and Zeng, X. (2022). Research on archaeology and digital restoration of costumes in spring outing painting of Madam Guo. Sustainability, 14(19), 12243. doi: 10.3390/su141912243.

[21] Zhu, C., Liu, K., Li, X., Zeng, Q., Wang, R., Zhang, B., Lü, Z., Chen, C., Xin, X. and Wu, Y. (2022). Research on archaeology and digital restoration of costumes in DaoLian painting. Sustainability, 14(21), 14054. doi: 10.3390/su142114054.

[22] Huang, H. (2011). Chinese clothing system and clothing style in previous dynasties. Jiangxi Fine Arts Publishing House, Nanchang.

[23] Guo, Z. (2015). A study on the costumes of immortals in the mural of Yongle Palace in the Yuan Dynasty. (Master dissertation). Tianjin Normal University, Tianjin, China.

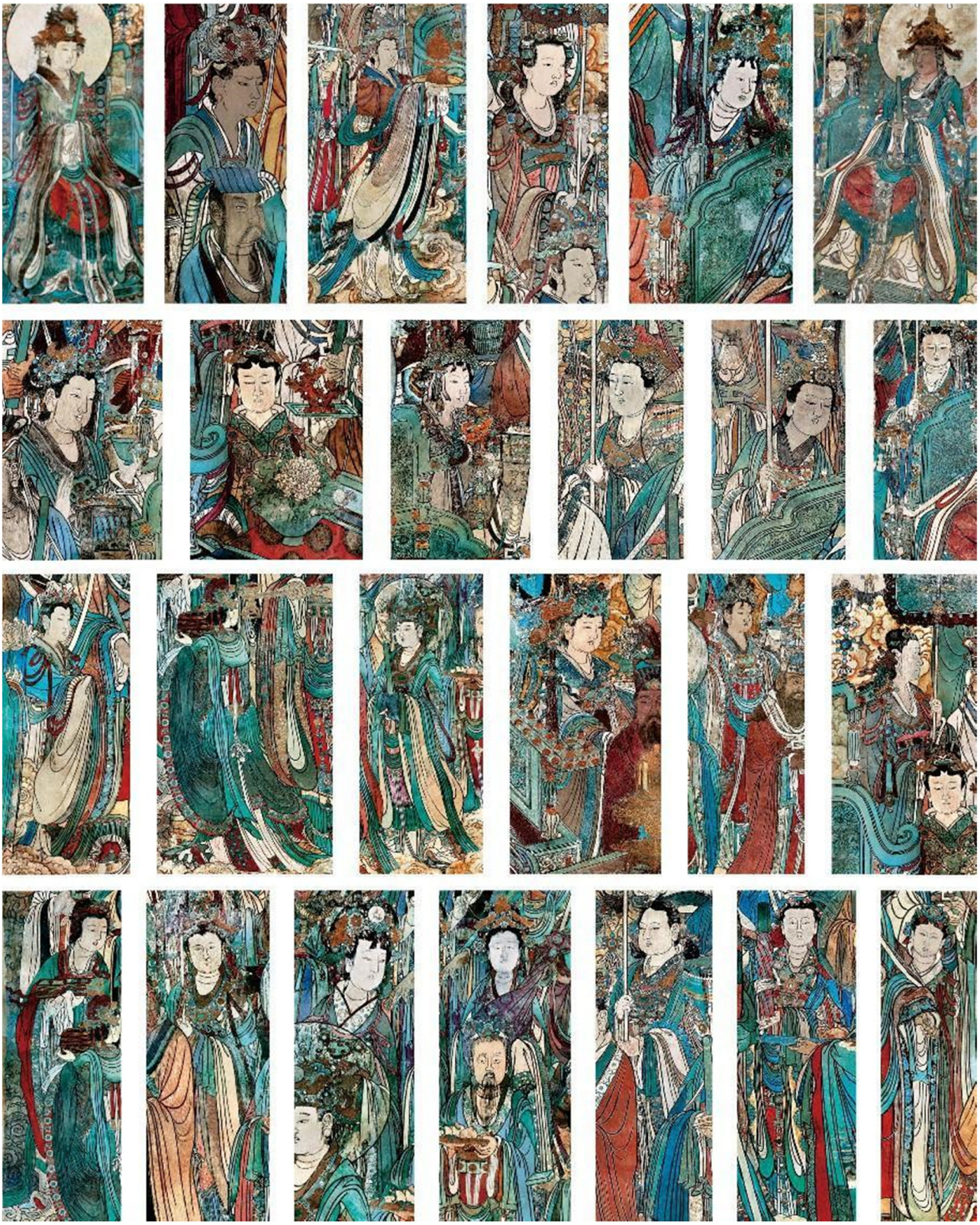
[24] Li, Y., Jiang, L. E. I., Li, X. and Feng, W. (2023). Non-contact clothing anthropometry based on two-dimensional image contour detection and feature point recognition. Industria Textila, 74(01), 67–73. doi: 10.35530/IT.074.01.202279.

[25] Sun, L. and Zhu, H. (2015). A study of human statures of skeletons found in Han, Tang and Song Dynasty tombs, Zhengzhou area. Acta Anthropologica Sinica, 34(3), 377–389. doi: 10.16359/j.cnki.cn11-1963/q.2015.0038.

[26] Yang, N., Zhang, M. and Liu, H. (2021). General theory of Hanfu: China Textile Press.

[27] Wang, S., Yin, Y., Chen, M., Wang, L., Wu, W. and Tang, J. (2013). Analysis on intelligent selection of characteristic parameters for back-up material for restoration of silk fabrics cultural relic. Journal of Silk, 50(10), 30–33 + 44. doi: 10.3969/j.issn.1001-7003.2013.10.007.

Appendix 1.



Images of 25 goddesses in worshiping

Appendix 2.

Language score quantitative table

Intensity of importance	Scale	Explanation
1	Equal importance	Indicates that two factors are of equal importance compared to each other.
3	Moderate importance	Indicates that the former is slightly more important than the latter when compared to the two factors.
5	Essential or strong importance	Indicates that the former is significantly more important than the latter when compared to the two factors.
7	Very strong importance	Indicates that the former is strongly more important than the latter when compared to the two factors.
9	Extreme importance	Indicates that the former is extremely more important than the latter when compared to the two factors.
2, 4, 6, 8	Between the above adjacent scales.	
Reciprocal	If the importance ratio of index i to index j is a_{ij}, then the importance ratio of index j to index i is $a_{ji} = 1/a_{ij}$.	

Appendix 3.

RI of random matrices

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Appendix 4.

Evaluation of virtual reconstruction effect

Please take a look at the following five images and compare the mural images and 3D virtual clothing models in each image. You can scan the QR code at the bottom right to view the 3D model from multiple angles. Evaluate the quality of a 3D virtual reconstruction model based on mural images. The more similar they are to the mural image, the closer the evaluation is to excellent.

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

1. Model appearance Z_1

	Excellent	Good	Average	Poor	Very poor
Make-up Z_{11}	○	○	○	○	○

2. Garment silhouette Z_2

	Excellent	Good	Average	Poor	Very poor
Zhongdan Z_{21}	○	○	○	○	○
large-sleeved robe Z_{22}	○	○	○	○	○
Skirt Z_{23}	○	○	○	○	○
Others Z_{24}	○	○	○	○	○

3. Garment fabrics Z_3

	Excellent	Good	Average	Poor	Very poor
Texture Z_{31}	○	○	○	○	○
Color Z_{32}	○	○	○	○	○
Pattern Z_{33}	○	○	○	○	○