Research on Digital Restoration of Plain Unlined Silk Gauze Gown of Mawangdui Han Dynasty Tomb Based on AHP and Human–Computer Interaction Technology

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Abstract: In 1972, the Plain Unlined Silk Gauze Gown unearthed from the Mawangdui Han Dynasty tomb in Changsha, Hunan Province, China, received attention from various fields such as archeology, cultural relics conservation, textile and costume because of its light texture and exquisite craftsmanship. However, due to it being unearthed decades ago and imperfect preservation measures being used, it has been increasingly damaged by the influence of the external environment. Therefore, there is an urgent need to carry out archeology, restoration and protection of the Plain Unlined Silk Gauze Gown. In this paper, the Plain Unlined Silk Gauze Gown is taken as the research object, and the costume pattern is obtained through 3D interactive pattern-making technology. Then virtual simulation technology is used to digitally restore the Plain Unlined Silk Gauze Gown in combination with the fabric, color and pattern of the costume. Finally, the Analytic Hierarchy Process (AHP) and the fuzzy comprehensive evaluation method are introduced to evaluate the virtual simulation effect of the costume. The results show that the virtual simulation effect of the Plain Unlined Silk Gauze Gown is very good. From the results of the costume restoration, the AHP captures the uncertainty in the process of costume virtual simulation evaluation, quantifies the judgments with weights, reduces the subjectivity of the evaluation process, and provides a scientific and effective method for evaluating the virtual simulation effect of ancient costumes.

Keywords: Plain Unlined Silk Gauze Gown; reverse engineering; human–computer interaction technology; virtual simulation; pattern making; AHP; fuzzy comprehensive evaluation method

1. Introduction

Silk is one of the major inventions of ancient China. Since Emperor Wu of the Western Han Dynasty (202 B.C.–220 A.D.) sent Zhang Qian on a mission to the West, silk produced in China began to be shipped abroad in large quantities and became a world-famous product. As an essential symbol of Chinese civilization, silk not only reflects the vital position in the economy, politics and trade but also reveals the development of ancient China’s ritual system, culture and art, customs and folklore and science and technology. In ancient times, the Silk Road was a commercial road across Asia and Europe, promoting cultural exchanges between the East and West and extensively promoting the process of human civilization, which highlight the unique status of silk.

The Mawangdui Han tomb is one of the top ten famous ancient tombs in the world. It was the family cemetery of Changsha Prime Minister Li Cang in the early Western Han Dynasty. Li Cang’s wife (Xin Zhui), Li Cang and Li Cang’s son are buried in Tombs 1–3, respectively. The tombs have undergone three archeological excavations since 1972, and a total of more than 3000 cultural relics, such as silk fabrics, silk books [1–3], silk paintings...
and lacquer [4] wares, have been unearthed, providing very important materials for the study of the history, culture, society and life of the Western Han Dynasty. Among the three tombs, Tomb 1 is the most civilized due to a well-preserved female corpse being unearthed. This female corpse was buried underground for two thousand years without decay. It can be said to be a rare miracle in the world, and it has extremely important value for subsequent biological and medical research [5–7]. The chamber of Tomb 1 consists of five parts, including four side chambers for storing items and a central coffin [4]. Among the many silk fabrics unearthed from Tomb 1, the most exquisite is the Plain Unlined Silk Gauze Gown, which has attracted worldwide attention. The Plain Unlined Silk Gauze Gown is now in the Hunan Provincial Museum. Although they are maintained by professionals, silk fabrics, as polymer materials, are vulnerable to light, heat, chemistry, biology, machinery and other factors, resulting in changes of in-hand feel, strength and color. Wang et al. studied the silk in the British Museum collection and developed the DMTA method for the conservation of ancient silk [8]. Garside et al. studied the influence of common silk weighing processes in Europe from the late 19th century to the early 20th century on the aging behavior of silk, so as to provide a scheme for the preventive protection of silk fabrics with historical collection significance [9]. However, the current technical means can only delay the aging of silk but cannot reverse the aging and damage of silk fabrics. There is also a lack of mature repair technology for aging silk fabrics.

From the perspective of cultural communication, the channel for people to understand and appreciate the Plain Unlined Silk Gauze Gown is mainly through the Internet in a search for relevant pictures, or to go to museums to see it, but these display methods are in the 2D plane—people can only see its front view and cannot do all-round viewing. Many institutions and universities have also noticed the issue of costume culture dissemination. Google has joined hands with 183 cultural institutions, including the Metropolitan Museum of Art, the Victoria and Albert Museum, China’s Beijing Costume Institute Museum of Ethnic Costume and China’s Silk Museum, to create the “We Wear Culture” project, featuring web pages on Google Arts & Culture that cover 3000 years of fashion culture. Such projects have served as a good example of spreading and enhancing the culture of costume, but they still fail to break the boundaries of 2D display.

With the rapid development of science and technology, costume virtual simulation technology has gradually approached the public vision, providing a digital solution for the conservation of rare costume and silk costume. Some researchers have focused on the reconstruction of 3D historical costume and have successively studied ancient costume restoration and virtual mannequins. The parametric historical model that was developed can be used to show corsets in the second half of the 19th century [10]. Costume restoration aspects include from 19th-century menswear restoration [11], the restoration of riding skirts in the late Victorian era [12] and the reconstruction of cage crinoline and skirt in the early 19th century [13] to the digital restoration of mail armor [14] and to the reconstruction of the military costume of Germanic soldiers in the second-fourth centuries [15]. The current study illustrates the feasibility of using virtual simulation of costume to restore valuable historical costume and provides a digital preservation method for silk fabrics that are prone to aging.

The digital restoration of cultural relics has gradually become a research hotspot in recent years [16,17]. Hou et al. proposed a novel method for the virtual restoration of cultural relics with a complex geometric structure based on multiscale spatial geometry [18]. Chu, Gao and Yang et al. applied virtual reality and deep learning technologies to study the classification, restoration and restoration of the fragments of the Terracotta Warriors [19–21]. Chen et al. proposed a method for modeling and supporting digital restoration based on unmanned aerial vehicle oblique photogrammetry combined with 3D laser scanning technology to restore the ancient watchtower complex in the Tibetan region of China [22]. Han et al. presented a non-destructive, more efficient and more scientific method that combines hyperspectral imaging and computer technology for the virtual digital restoration of a bronze chariot’s patterns [23]. Hou et al. proposed a virtual restoration method
The digital restoration of costumes can improve people’s viewing satisfaction, attract more potential viewers, and realize the protection and cultural dissemination of rare historical costumes. Many research institutions are committed to continuously improving technology to achieve a more realistic costume simulation effect. Therefore, it is necessary to evaluate the virtual simulation effect of the costume. At present, there is no unified evaluation standard for the costume virtual simulation effect, which is mostly completed by qualitative and subjective methods, and the scientific conclusion is difficult to guarantee. In the early 1970s, American operations research scientist Saaty put forward the famous Analytic Hierarchy Process (AHP), which decomposes the problem into different constituent factors, then aggregates and combines the factors according to different levels according to the correlation, influence and subordinate relationship between the factors, and forms a multilevel analysis structure model, which provides a new idea for the problems that are difficult to describe quantitatively [42,43]. The fuzzy set theory proposed by Zadeh in 1965 provides a solution to the problem without boundary [44]. In recent years, a reciprocal of the AHP combined the AHP with fuzzy set theory, the so-called fuzzy AHP [45]. In the field of costumes, the AHP provides solutions to many problems such as the selection of supply chains and suppliers [46–48], the online shopping recommendation system [49] and fabric selection [50]. However, it is seldom applied to the evaluation of virtual simulation costumes.
In the process of the literature review, we found that the above studies are still inadequate, mainly in four aspects. First, few people study the digital restoration of Chinese historical costumes. Secondly, the restoration process of the pattern is more complex in the process of historical costume restoration. Moreover, the method of restoration cannot be used for reference to the restoration of other costume patterns. Finally, the results of digital restoration lack unified and quantitative evaluation standards, so it is difficult to ensure the accuracy of restoration.

Based on previous studies, we used the research method of 3D interactive costume pattern-making technology to obtain the pattern of the Plain Unlined Silk Gauze Gown [41]. The costume pattern obtained was then modified in conjunction with the study of the Plain Unlined Silk Gauze Gown, we further used the virtual simulation technology to carry out 3D digital restoration and we finally evaluated the virtual simulation effect of the Plain Unlined Silk Gauze Gown based on the AHP and the fuzzy comprehensive evaluation method [45,51,52].

In order to construct a clear article structure, the paper is organized as follows: Section 2 introduces the general scheme of this paper. Section 3 carries out the archeological study of the Plain Unlined Silk Gauze Gown and the 3D human–computer interaction pattern-making process as well as the costume virtual simulation process were conducted. Section 4 introduces how to evaluate the effect of costume restoration using the AHP model and the fuzzy comprehensive evaluation method. Section 5 discusses 3D human–computer interaction pattern-making technology and the AHP evaluation method. Finally, Section 6 summarizes some conclusions.

2. General Scheme

The method of this paper was to gradually complete the 3D digital Plain Unlined Silk Gauze Gown based on 2D images, then build an evaluation system and determine the index weight based on the fuzzy comprehensive evaluation to evaluate the virtual display effect. Our research was mainly divided into four parts, as shown in Figure 1.

Figure 1. Digital restoration process of the Plain Unlined Silk Gauze Gown.

- The Plain Unlined Silk Gauze Gown was analyzed and studied from five aspects: structure, size, fabric, color and pattern.
- The outline of the Plain Unlined Silk Gauze Gown was extracted and put into a 3D environment for virtual fitting. The paper pattern was developed by human-
computer interaction technology, including hardening, structural line drawing, 3D unfolding, and correct pattern.

- Virtual simulation technology was used to conduct virtual fitting and display the restoration effect.
- The simulation effect was evaluated based on the AHP and the fuzzy comprehensive evaluation method, and the similarity between the restoration result and the historical prototype was proved.

3. Method

3.1. Recovery Object Analysis

3.1.1. Structural Analysis

The Plain Unlined Silk Gauze Gown with Straight Lapel of the Western Han Dynasty was unearthed in Tomb 1 of the Han Dynasty in Mawangdui, Changsha, Hunan Province, China, in 1972. The tomb’s owner is Xin Zhui, the wife of Li Cang, the Prime Minister of Changsha in the early Western Han Dynasty. The costume is now kept in the Hunan Provincial Museum (Figure 2a). It is the lightest, thinnest and earliest treasure so far. It can be said to be the peak work of textiles in the Western Han Dynasty (202 B.C.–8 A.D.). Most scholars believe that it should be worn outside the brocade robe, which can increase its gorgeous and hazy beauty. Some scholars think it is underwear. The Gauze Gown is a kind of costume in the Chinese costume system, that is, an unlined single-layer costume, which is usually divided into a diagonal lapel (Figure 2b) and a straight lapel (Figure 2c). Both diagonal lapel and straight lapel belong to deep dress. The skirt of the diagonal lapel is long, and the lengthened skirt is triangular, which is wound to the front after passing through the back. The skirt of the straight lapel is not as long as that of the diagonal lapel, the hem is cut vertically, and the lapel is on the side or behind the side of the body.

The Plain Unlined Silk Gauze Gown is a cross collar, right lapel and straight lapel, similar to the deep dress with upper and lower costume connected in the Han Dynasty, and the cuffs are wide. Except for the collar and cuffs decorated with brocade, the whole costume is made of single yarn without lining. Therefore, it is recorded in the history books as the Plain Unlined Silk Gauze Gown. There are seven patterns of the Plain Unlined Silk Gauze Gown in total, including four pieces of the top and three pieces of the bottom. The pattern composition is shown in Figure 2d.
3.1.2. Confirmation of Size

The length of the Plain Unlined Silk Gauze Gown is 128 cm, the length of the through sleeves is 195 cm and the whole body’s weight is only 49 g. It can be said that it is as light as smoke and as thin as cicada wings. The reason for its lightness is not that the yarn hole of the fabric is large but because the yarn is very thin. A 900 m long silk weighs about 1 g. The superb production technology of the Plain Unlined Silk Gauze Gown represents the highest level of silkworm rearing, silk reeling and weaving technology in the early Western Han Dynasty. In this paper, the proportional distribution method was used to obtain the data on each part of the costume. As shown in Figure 3, first the outline of the costume through the front picture of the Plain Unlined Silk Gauze Gown was extracted, with the actual through sleeve length being $N$, the through sleeve length in the line drawing being $n$ and the length of a part in the line drawing being $m$. The actual size, $M$, can be deduced, that is, $M = \frac{nm}{N}$, so as to determine the data of each essential part of the Plain Unlined Silk Gauze Gown.
3.1.3. Research on Fabric, Color and Pattern

The Mawangdui Han tomb is rich in excavated physical materials, especially the unearthed textiles. Although the textiles have experienced more than 2000 years of history, they are still well preserved, bright in color and firm in texture. Cotton was not popular in the Western Han Dynasty, so silk and linen were mostly costume materials at that time. The silk-weaving technology of the Han Dynasty reached a reasonably high level. There are many kinds of silk fabrics with exquisite skills, including plain yarn, yarn, brocade, faille and so on. Among them, plain yarn was the most common silk fabric at that time. Brocade is made of colored silk yarn bleached and dyed in advance. It is a high-grade silk fabric with a silky luster and represents the superb level of silk-weaving technology in the Western Han Dynasty. According to the physical records unearthed from Mawangdui Han Tomb 1, in addition to the Plain Unlined Silk Gauze Gown, there are dozens of silk fabrics such as silk scarves, silk, silk shoes and embroidered silk brocade robes.

The Western Han Dynasty has the earth virtue of saying, earth virtue represents the merit of the earth, so in color a more esteemed yellow. During the Western Han Dynasty, the dyeing process was quite developed. Only the silk fabrics excavated from Mawangdui Han Tomb 1 had many colors, including vermilion, dark brown, camel, violet, dark green, light brown, etc. According to statistics, there were as many as thirty-six colors. At that time, dyeing mainly used vegetable dyes and mineral dyes. These colors are made of red, yellow and blue primary colors in a certain proportion and then processed by the dip-dyeing and mordanting technique. The dresses of the emperor’s officials were mainly colored with red, yellow, white, blue and black, while the people’s dresses were generally single-colored, with linen white and black as the primary colors.

From the numerous embroideries produced in Tomb 1 (Figure 4), it can be seen that the mortuary costume of Xin Zhui, the wife of the tomb owner, was mainly in yellow tones, supplemented by silver-gray, silver-white, gold, vermillion, light brownish-red, olive green, purple-gray, dark green and other colors. In terms of patterns, they liked to use flames, hills, clouds, flowers, birds and different designs with good meanings to send their feelings. Taking longevity embroidery (Figure 4B) as an example, the patterns of flower ears and flowing clouds are embroidered on brown silk with light brown-red, olive green and other multicolor silk threads. In ancient China, the long-tail flowing clouds symbolized the tail of the longevity bird, so they also conveyed the meaning of longevity.

When the Plain Unlined Silk Gauze Gown with straight lapel was unearthed, the edge of the costume was dark brown and the primary color was light brown-yellow. The color of the costume may be different from that of the original object, considering that the silk fabric is prone to yellowing and oxidation accelerates yellowing when it is unearthed due to poor light resistance.
3.2. Human–Computer Interactive Costume Pattern-Making Technology

An accurate 2D pattern is a basis for successfully restoring historical costumes. The traditional pattern-making process requires not only rich costume structure theory but also enough experience. Human–computer interactive technology can well break the pain point and improve the efficiency of traditional pattern making. This section mainly uses software Design Concept to realize human–computer interactive pattern making. The specific steps are as follows (Figure 5):
Firstly, adopt the costume construction idea based on pattern [31] and sketch [32–34], import the photos of the Plain Unlined Silk Gauze Gown into the drawing software (Adobe Illustrator), extract the outer contour lines of the costume and delete the internal structure except for the contour lines, so as to obtain the 2D contour line of the costume (Figure 5b). The purpose of this step is to obtain the costume outline, and there is no requirement for accurate data on the costume pattern, so the technical requirements for the operator can be reduced.

Then, import the extracted front and back contours of the costume into CLO Standalone, reasonably arranged around the mannequin, and stitch them together by using virtual stitching technology to generate the initial 3D costume surface.

Moreover, the costume surface will be wrinkled and unsmooth due to the influence of factors such as the pattern space gap. Therefore, the initial 3D costume surface needs to be adjusted to make the 3D surface as close to the historical prototype as possible. The adjustment of the 3D surface makes the costume as flat as possible.

However, the 3D surface will still have vertical folds caused by gravity and other factors. The existence of these folds hinders the drawing of structural lines on the costume surface. Stretching and freezing can well avoid the uncertainty, remove virtual gravity and reduce unnecessary vertical folds without changing the edge of the costume and its triangular grid area.

After hardening and freezing, import the costume model into the software Design Concept, and draw the internal structure line of the costume on the hardened and frozen 3D costume surface in combination with the structure studied in Section 3.1.1.

In addition, flatten the 3D surface according to the drawn dividing line to obtain the initial costume pattern.

Finally, combined with the dimensions of the critical parts of the Plain Unlined Silk Gauze Gown determined in Section 3.1.2, correct the obtained pattern to obtain an accurate Plain Unlined Silk Gauze Gown pattern.

3.3. Virtual Simulation of Plain Unlined Silk Gauze Gown

This section uses the software CLO Standalone, which can provide a 2D and 3D linkage environment and combine the style, fabric, color, pattern and other aspects of the
costume to perform a virtual simulation of the Plain Unlined Silk Gauze Gown. The specific steps are as follows (Figure 6):

![Figure 6. Virtual Simulation Flowchart.](image)

Firstly, in order to better restore and display the virtual simulation costume, the 3D human body model needs to be adjusted. According to unearthed documents, Xin Zhui, the owner of the Plain Unlined Silk Gauze Gown, was 154 cm tall. Therefore, adjust the height of the parametric mannequin that comes with CLO Standalone to 154 cm.

Then, in order to make the restoration effect appear better, adjust the posture of the virtual model to the state of spreading both arms.

Moreover, the developed Plain Unlined Silk Gauze Gown costume is introduced into the 2D and 3D linkage interface, and the pattern is reasonably arranged around the human body.

In addition, add virtual sewing thread to the corresponding pattern. Pay attention to the consistency of the direction of the sewing thread here. Otherwise, there will be pumping pleats and other conditions.

Then, perform virtual stitching and adjustment of the pattern.

Additionally, the color of the simulated costume should be set in a 3D environment according to the color extracted from the Plain Unlined Silk Gauze Gown.

Furthermore, the fabric properties and pattern texture of the costume affect the fidelity of the costume, and the light and thin texture of the Plain Unlined Silk Gauze Gown is also closely related to the material of the fabric. To this end, this paper used computer-aided means to convert costume patterns into gray-scale images through Matlab software and form the matrix of this image. Each pixel in the image was represented by a number \( x(x \in [0, 255]) \) in the matrix. The number 255 represents a white pixel, any pixel that is not 255 is black and the number of black pixels was divided by the total number of pixels to calculate the pattern area of 2.558 m². Combining the fabric settings (Figure 7a), the costume is closer to 49 g.

Finally, the 3D virtual display of the Plain Unlined Silk Gauze Gown is shown in Figure 7b.
4. Evaluation of Costume Virtual Simulation Effect

4.1. Establishing the Evaluation Index System

The purpose of costume virtual simulation effect evaluation is to provide information feedback to technicians to improve the quality of costume virtual simulation. However, there is a lack of a unified evaluation standard of costume virtual simulation, which is mainly through the subjective evaluation of technicians. The evaluation method is largely superficial and lacks scientific and objectivity, which is not conducive to the dissemination of costume culture. Therefore, a scientific and objective evaluation method is urgently needed to improve the accuracy of costume virtual simulation.

This paper evaluated the virtual simulation effect of the Plain Unlined Silk Gauze Gown based on the theoretical basis of the AHP. Virtual simulation is a digital restoration of costume objects based on many data query, literature retrieval and experience summary. To accurately reflect the effect of virtual simulation, we need to build the evaluation index system from multiple angles and levels. Based on the principle of “clear hierarchy, concise and scientific”, the objective level was divided into 3 primary indicators ($U_i$) and 11 secondary indicators ($U_{ij}$), as shown in Figure 8.

Figure 7. Effect display.

Figure 8. Virtual simulation effect evaluation index system.
4.2. Establishing Judgment Matrix

After constructing the evaluation system, we needed to further determine the index weight. When determining the weights between factors at each level, a single qualitative result is usually not easily accepted. The consistent matrix method proposed by Saaty no longer compares all factors together but compares them with each other. The relative scale reduces the difficulty of comparing factors with different natures and improves the accuracy of comparison.

Five experts were invited to form a review group, and the evaluation given by each expert was quantified by using the 1–9 quantile scale method. Table 1 gives the quantitative table of language scores suggested by the 1–9 quantile scale method.

| 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 \( a_{ji} = \frac{1}{a_{ij}} \). |

After quantifying the expert opinions, we achieved a positive and reciprocal judgment matrix formed by pairwise comparison \( A \) as shown in Formula (1):

\[
A = (a_{ij})_{n \times n} = \begin{pmatrix}
a_{11} & \cdots & a_{1n} \\
\vdots & \ddots & \vdots \\
a_{n1} & \cdots & a_{nn}
\end{pmatrix}
\]  
(1)

In Formula (1), \( a_{ij} \) represents the importance comparison results of element \( i \) and element \( j \), where \( a_{ij} = \frac{1}{a_{ji}} > 0 \), \( a_{ii} = 1 \). \( A \) is denoted as the judgment matrix formed by comparing the factors under the objective level \( U = (U_1, U_2, U_3) \) and \( A_i (i = 1, 2, 3) \) then denotes the positive and reciprocal judgment matrix formed by pairwise comparison of each factor \( U_{ij} \) under the primary indicators \( U_j \). In this section, the judgment matrix obtained by the first expert after scoring is given, as shown in Tables 2–5.

Table 2. Judgment matrix \((A)\) of the primary indicators.

| \( U_1 \) | \( U_2 \) | \( U_3 \) |
|----------|----------|----------|
| \( U_1 \) | 1.000    | 1.000    | 2.000    |
| \( U_2 \) | 1.000    | 1.000    | 2.000    |
| \( U_3 \) | 0.500    | 0.500    | 1.000    |
Table 3. Judgment matrix \( (A_1) \) of the secondary indicators within “Overall shape” \( (U_1) \).

|          | \( U_{11} \) | \( U_{12} \) |
|----------|--------------|--------------|
| \( U_{11} \) | 1.000        | 0.500        |
| \( U_{12} \) | 2.000        | 1.000        |

Table 4. Judgment matrix \( (A_2) \) of the secondary indicators within “Costume structure” \( (U_2) \).

|          | \( U_{21} \) | \( U_{22} \) | \( U_{23} \) | \( U_{24} \) | \( U_{25} \) |
|----------|--------------|--------------|--------------|--------------|--------------|
| \( U_{21} \) | 1.000        | 2.000        | 3.000        | 4.000        | 1.000        |
| \( U_{22} \) | 0.500        | 1.000        | 2.000        | 3.000        | 0.500        |
| \( U_{23} \) | 0.333        | 0.500        | 1.000        | 2.000        | 0.333        |
| \( U_{24} \) | 0.250        | 0.333        | 0.500        | 1.000        | 0.250        |
| \( U_{25} \) | 1.000        | 2.000        | 3.000        | 4.000        | 1.000        |

Table 5. Judgment matrix \( (A_3) \) of the secondary indicators within “Costume fabric” \( (U_3) \).

|          | \( U_{31} \) | \( U_{32} \) |
|----------|--------------|--------------|
| \( U_{31} \) | 1.000        | 2.000        |
| \( U_{32} \) | 0.500        | 1.000        |
| \( U_{33} \) | 2.000        | 4.000        |

4.3. Hierarchical Ranking and Consistency Checking

The so-called hierarchical single ranking refers to the ranking of the importance of each factor at the level for a factor at the previous level. It is represented by the eigenvector of the judgment matrix. That is, 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. This process is called hierarchical single ranking.

Initially, for judgment matrix \( A_i \), calculate the eigenvector corresponding to the eigenvalue satisfying Formula (1). Then, normalize the eigenvector to the vector \( W \), and the component of \( W \) is the weight of the single ranking of the corresponding elements.

\[
AW = \lambda_{\text{max}} W \tag{2}
\]

Therefore, the characteristic roots \( \lambda'_{\text{max}}, \lambda'_{\text{max}1}, \lambda'_{\text{max}2}, \lambda'_{\text{max}3} \) and their corresponding weight vector \( W'_1, W'_2, W'_3, W'_4 \) in Tables 2–5 are obtained by calculation using Formula (1) as follows:

\[
\lambda'_{\text{max}} = 3.000, \quad W'_1 = (W'_{u11}, W'_{u12}, W'_{u13})^T = (0.4000, 0.4000, 0.2000)^T
\]

\[
\lambda'_{\text{max}1} = 2.000, \quad W'_2 = (W'_{u21}, W'_{u22})^T = (0.3333, 0.6667)^T
\]

\[
\lambda'_{\text{max}2} = 5.036, \quad W'_3 = (W'_{u31}, W'_{u32}, W'_{u33}, W'_{u34}, W'_{u35})^T = (0.3192, 0.1840, 0.1093, 0.0683, 0.3192)^T
\]

\[
\lambda'_{\text{max}3} = 3.000, \quad W'_4 = (W'_{u41}, W'_{u42})^T = (0.2857, 0.1429, 0.5714)^T
\]

Additionally, the consistency test needs to be carried out in order to ensure the coordination among the elements in the judgment matrix \( A \) (Formula (3)). Here, the consistency index \( (CI) \) is introduced and calculated, and the specific expression is shown in Formula (4). In Formula (4), \( \lambda_{\text{max}} \) is the maximum eigenvalue of the judgment matrix, and \( n \) is the order of the matrix.

\[
a_{ij} \cdot a_{jk} = a_{ik} \tag{3}
\]

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1} \tag{4}
\]
Furthermore, according to Formula (5), the consistency ratio (CR) is the ratio of the consistency index (CI) of the judgment matrix to the average random consistency index (RI), where the average RI depends on the order (n) of the matrix, as shown in Table 6.

\[ CR' = \frac{CI}{RI} \]  

(5)

**Table 6.** Random consistency index (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 |

When \( CR \leq 0.1 \), it is considered that the consistency check of hierarchical single ranking is passed, otherwise experts need to compare repeatedly and then modify and recalculate the judgment matrix. The results of the hierarchical single ranking consistency check for the first expert are given in Table 7.

**Table 7.** Consistency check results of hierarchical single ranking of the first expert.

| Matrix | \( \lambda_{max} \) | CI | \( CR' \) | Consistency Check Result |
|--------|---------------------|----|-----------|--------------------------|
| A      | 3.000               | 0  | 0         | Pass                     |
| A\(_1\) | 2.000              | 0  | 0         | Pass                     |
| A\(_2\) | 5.036              | 0.0091 | 0.0081 | Pass                     |
| A\(_3\) | 3.000              | 0  | 0         | Pass                     |

In the whole process of the AHP, in addition to the consistency check of each judgment matrix, the so-called consistency check of hierarchical total ranking should also be carried out. The consistency check of hierarchical total ranking can be carried out layer by layer according to Formula (6). The consistency check results of the hierarchical total ranking of five experts are given in Table 8.

\[ CR = \frac{\sum_{i=1}^{n} w_i c_i}{\sum_{i=1}^{n} w_i r_i} \]  

(6)

**Table 8.** Consistency check results of hierarchical total ranking of five experts.

| Expert       | \( CR \) | Consistency Check Result |
|--------------|---------|--------------------------|
| First Expert | 0.0066  | Pass                     |
| Second Expert| 0.0112  | Pass                     |
| Third Expert | 0.0131  | Pass                     |
| Fourth Expert| 0.0200  | Pass                     |
| Fifth Expert | 0.0159  | Pass                     |

When all the consistency checks of the hierarchical total ranking passed (\( CR \leq 0.1 \)), the weight vectors of the five experts’ scoring results were synthesized by arithmetic averaging to obtain the weight vector \( W \) for the primary indicator and the weight vectors \( W_1, W_2, W_3 \) for the secondary indicator. The weight vector of the “Primary indicators” was calculated as:

\[ W = (W_{11}, W_{12}, W_{13})^T = (0.45524, 0.33000, 0.21476)^T \]

The weight vector of “Overall shape” was calculated as:

\[ W_1 = (W_{111}, W_{112})^T = (0.38332, 0.61668)^T \]

The weight vector of “Costume structure” was calculated as:
\[ W_2 = \left( W_{U_21}, W_{U_22}, W_{U_23}, W_{U_24}, W_{U_25} \right)^T \\
= \left( 0.39084, 0.21600, 0.15134, 0.10356, 0.13828 \right)^T \]

The weight vector of “Costume fabric” was calculated as:
\[ W_3 = \left( W_{U_31}, W_{U_32}, W_{U_33} \right)^T = \left( 0.48882, 0.21274, 0.29844 \right)^T \]

The above weight vectors were collated to obtain the weight coefficient diagram of the virtual simulation effect of the Plain Unlined Silk Gauze Gown (Figure 9).

Figure 9. Weight coefficient diagram of the virtual simulation effect.

4.4. Fuzzy Comprehensive Evaluation

Fuzzy sets were extended based on classical sets, and the 0 and 1 system of classical sets was developed as any map from the theoretical domain to the closed interval \([0, 1]\), making the classical sets more scientific. Fuzzy comprehensive evaluation is an application of fuzzy mathematics, which can make an overall judgment of things that have multiple attributes or whose overall merit is influenced by multiple factors, combining these attributes or factors.

In order to improve the objectivity of the evaluation results, the elements in the secondary indicators were evaluated, and the factor set was: \(U_{ij} = \{U_{i1}, U_{i2}, U_{i3}, \ldots, U_{i3}\}\). In the study, the evaluation comment set was divided into five levels: \(V = \{\text{very good, good, average, poor and very poor}\}\), and then the factor set \(U_{ij}\) was evaluated and the single factor evaluation matrix \(R\) from \(U_{ij}\) to \(V\) was established: \(R = (r_{ij})_{nxm}\). That is:

\[
R = (r_{ij})_{nxm} = \begin{bmatrix}
    r_{11} & r_{12} & r_{13} & \ldots & r_{1m} \\
    r_{21} & r_{22} & r_{23} & \ldots & r_{2m} \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    r_{n1} & r_{n2} & r_{n3} & \ldots & r_{nm}
\end{bmatrix}
\]

According to the factor set and comment set proposed above, we collected the opinions of costume teachers and students on the virtual simulation effect of the Plain Unlined Silk Gauze Gown and formed an evaluation matrix of each index. Fuzzy vector \(R_i\) \((i = 1, 2, 3)\) represents the degree of membership of fuzzy subsets at each level from different factors. To construct matrix \(R_3\) as an example, when considering the “Costume silhouette”, 39% of the respondents rated it as “very good”, 46% rated it as “good”, 15% rated it as “average” and 0% rated it as “poor” or “very poor”. When considering “Costume style”, 58% of respondents rated it as “very good”, 38% rated it as “good”, 4% rated
it as “average” and 0% rated it as “poor” or “very poor”. Therefore, the following matrix \( R \) can be derived:

\[
R_1 = \begin{bmatrix}
0.39 & 0.46 & 0.15 & 0 & 0 \\
0.58 & 0.38 & 0.04 & 0 & 0
\end{bmatrix}
\]

Similarly, matrix \( R_2 \) and matrix \( R_3 \) can be obtained as follows:

\[
R_2 = \begin{bmatrix}
0.35 & 0.58 & 0.07 & 0 & 0 \\
0.46 & 0.39 & 0.15 & 0 & 0 \\
0.66 & 0.19 & 0.15 & 0 & 0 \\
0.62 & 0.38 & 0 & 0 & 0 \\
0.27 & 0.42 & 0.23 & 0.04 & 0.04
\end{bmatrix}
\]

\[
R_3 = \begin{bmatrix}
0.39 & 0.46 & 0.15 & 0 & 0 \\
0.42 & 0.39 & 0.19 & 0 & 0 \\
0.39 & 0.46 & 0.15 & 0 & 0
\end{bmatrix}
\]

The weight is the proportion of each evaluation factor in the evaluation index system according to its relative importance. The weight distribution set \( W \) can be regarded as the fuzzy set of \( U \) set. Multiply the factor weight vector with the single factor evaluation matrix to obtain the evaluation result \( B \):

\[
B = W \cdot R = (b_1, b_2, b_3, \ldots, b_n)
\]

where \( B \) is the evaluation result based on all factors in index system \( U \). According to Formula (7), we obtained the evaluation results of the \( U_1 \) as follows:

\[
B_1 = W_1 \cdot R_1 = (0.38332, 0.61668) \cdot \begin{bmatrix}
0.39 & 0.46 & 0.15 & 0 & 0 \\
0.58 & 0.38 & 0.04 & 0 & 0
\end{bmatrix} = (0.5072, 0.4107, 0.0822, 0, 0)
\]

Similarly, we obtained the evaluation results of \( U_2 \) and \( U_3 \) through the following calculation:

\[
B_2 = W_2 \cdot R_2 = (0.4376, 0.4371, 0.1143, 0.0055, 0.0055)
\]

\[
B_3 = W_3 \cdot R_3 = (0.3964, 0.4451, 0.1585, 0, 0)
\]

The evaluation matrix \( R \) of the target layer is established according to the above matrix as follows:

\[
R = \begin{bmatrix}
B_1 \\
B_2 \\
B_3
\end{bmatrix} = \begin{bmatrix}
0.5072 & 0.4107 & 0.0822 & 0.0000 & 0.0000 \\
0.4376 & 0.4371 & 0.1143 & 0.0055 & 0.0055 \\
0.3964 & 0.4451 & 0.1585 & 0.0000 & 0.0000
\end{bmatrix}
\]

The evaluation matrix \( R \) represents the membership value of each evaluation, which is related to each factor in the secondary index. Therefore, the comprehensive evaluation calculation of the virtual simulation effect of the Plain Unlined Silk Gauze Gown is as follows:

\[
B = W \cdot R = (0.45524, 0.33000, 0.21476)
\]

\[
B = \begin{bmatrix}
0.5072 & 0.4107 & 0.0822 & 0 & 0 \\
0.4376 & 0.4371 & 0.1143 & 0.0055 & 0.0055 \\
0.3964 & 0.4451 & 0.1585 & 0 & 0
\end{bmatrix} = (0.4604, 0.4268, 0.1092, 0.0018, 0.0018)
\]

According to the results of the fuzzy comprehensive evaluation, the overall shape restoration effect of the Plain Unlined Silk Gauze Gown is very good, and its membership degree is 50.72%. The restoration effect of the costume structure is very good, and its membership degree is 43.76%. The restoration effect of the costume fabric is good, and its membership degree is 44.51%. Overall, the restoration effect of the Plain Unlined Silk Gauze Gown is very good, the membership degree is 46.04%, the good membership degree is 42.68%, the average membership degree is 10.92%, the poor membership degree is 0.18%
and the very poor membership degree is 0.18%. According to the principle of maximum membership degree, the virtual simulation effect of the Plain Unlined Silk Gauze Gown is very good.

5. Discussion

The results of the excavation of Mawangdui Han tomb were a shock. There are two things from that excavation that have become world famous. One is a female corpse that had been preserved for thousands of years, and the other is the discovery of the Plain Unlined Silk Gauze Gown as thin as a cicada’s wings. There have been many studies on the female corpse and its preservation environment [5–7], but there have been few studies on the Plain Unlined Silk Gauze Gown. From the perspective of scientific and technological archeology, this paper studied the structure, color, fabric and pattern of the Plain Unlined Silk Gauze Gown and combined pattern-making technology of human–computer interaction and virtual simulation technology to digitally restore the Plain Unlined Silk Gauze Gown. Compared with traditional silk fabric protection technology [8,9], the color of the clothes produced by virtual simulation is more vivid and durable. Compared with the traditional digital restoration of rigid cultural relics [16–25], the research method combining reverse engineering and virtual simulation proposed in this paper provides a reference for the digital restoration of flexible cultural relics.

From the perspective of costume archeology, the restoration of historical costumes requires practitioners to have a rich theoretical basis and practical experience in pattern making. Therefore, traditional costume restoration has always had the problems of low efficiency, a long cycle and poor effect. Pattern-making methods based on patterns and sketches can reduce the difficulty of this method [31–34]. Virtual simulation technology provides new ideas for the preservation and dissemination of historical costume [10–15]. However, previous research mainly focuses on delivering digital means for the restoration of ancient costumes and does not propose a unified standard to verify the similarity between the restored costumes and historical prototypes. In this context, this paper introduced the pattern-making method based on the sketch, combined this method with costume virtual simulation technology to form a closed-loop operation process of 2D–3D–2D–3D–3D and finally evaluated the costume restoration by using the mathematical model of the combination of the AHP and the fuzzy comprehensive evaluation method to ensure the accuracy of the restoration results.

This study mainly included five processes, 2D–3D, 3D–2D, 2D–3D, 3D–3D, and constructed an evaluation system. The 2D–3D process stitched the extracted costume contour to generate a 3D costume contour. The 3D–2D process used costume-flattening technology to unfold the 3D costume surface to generate the costume pattern. The 2D–3D process modified the pattern obtained in the previous step and carried out virtual simulation again. The 3D–3D process set the attributes of the virtual simulation results to achieve the ideal effect. Finally, based on the principle of “clear hierarchy, concise and scientific,” an evaluation system of 3 primary and 11 secondary indicators were constructed to evaluate the restoration results.

To sum up, this study verifies the realizability of the closed-loop operation process of 2D–3D–2D–3D–3D in the process of costume archeology and provides a new idea for costume archeology. In addition, it proves that the mathematical model combined with the AHP and the fuzzy comprehensive evaluation method is realizable in evaluating the effect of costume restoration, which brings a new perspective to the evaluation effect of ancient costume restoration. However, this study is not perfect. Its limitations mainly lie in that when there are too many indicators of the evaluation object, the data statistics are significant and the weight is difficult to determine. In addition, the index system needs the support of an expert system. If the index given is unreasonable, the accuracy will also be affected. It is suggested that attention must be paid to the division of the index layer when evaluating the effect of costume with a complex structure.
6. Conclusions

Costume virtual simulation technology is an effective means to preserve rare ancient costumes, so it is widely used and highly valued by the costume industry. As the most delicate and light silk fabric unearthed from the Mawangdui Han tomb, the Plain Unlined Silk Gauze Gown is in urgent need of conservation because it is not in as good a condition as it used to be because of time, environment and climate.

In this paper, the method of 3D–2D–3D was applied to the digital restoration of the Plain Unlined Silk Gauze Gown. The restoration results were evaluated by the AHP and the fuzzy comprehensive evaluation method to reduce the subjectivity in the evaluation process. The research method used in this paper has the following four advantages: (1) From the perspective of cherishing cultural relics protection, this paper provides a digital protection technology for cherishing costumes so that the exquisite costume is no longer damaged by time and environmental factors and can survive forever. This lays the foundation for a 3D digital costume museum. (2) From the perspective of costume culture communication, the digitally restored costume breaks through the traditional 2D exhibition form and is presented in 3D form of “omnidirectional and multilayer”. The viewer can see the details of the Plain Unlined Silk Gauze Gown more comprehensively, which enhances the interaction. (3) From the perspective of pattern making, the human–computer interaction technology we used improves efficiency and reduces the difficulty of pattern making. The method provides a reference for pattern making in costume archeology. (4) From the simulation results, the AHP model and the fuzzy comprehensive evaluation method were used to verify the real results. Our proposed method captures the fuzziness of judgment, quantifies the weight of judgment and makes the results more objective and reasonable. The verification results show the similarity between the restored costume and the historical prototype and improve the reliability of the results. Our proposed method can reduce subjectivity in the evaluation process and provide a scientific and effective method for the restoration evaluation of ancient costume.

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