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Ancient thangka Buddha face recognition based on the Dlib machine learning library and comparison with secular aesthetics

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Abstract

Presently, face recognition technology is rapidly advancing and has emerged as a crucial field of research. Thangka, being a significant repository of Buddhist imagery, encompass a vast amount of Buddha image data depicting diverse Buddhist themes from various historical epochs. Accurate recognition of facial features in these Buddha images is particularly significant in comprehending the historical evolution of thangka, especially the facial features correlation between Buddha society and secular society. Hence, in this study, 68 facial feature points was employed to obtain using the Dlib deep learning library, from which 16 facial geometric feature indices were derived. These indices served as the foundation for the establishment of a facial measurement standard and aesthetic evaluation index for thangka Buddha. A meticulous evaluation and identification of thangka facial details spanning nearly a millennium were conducted, and the transformation of thangka facial features was analyzed and deliberated from a secular aesthetic perspective. Upon conducting this study, it was discovered that: (1) The deep learning library exhibited effective performance in identifying facial characteristics in thangka Buddha images, and the facial evaluation index proved to be a reliable tool for evaluating both measurement standards and aesthetics. (2) The facial measurement standards depicted in thangka Buddha images have evolved and become increasingly standardized over time, maintaining a highly symmetrical aesthetic. (3) The aesthetic of thangka facial features draw upon the secular Tibetan face as their primary reference(Euclidean distance is 0.42), however, during the 17-19th centuries, Han Chinese facial features were gradually incorporated(Euclidean distance is 0.492), and the degree of fusion between Han Chinese and Tibetan facial aesthetics has become more profound.

Keywords Face recognition, Thangka Buddha, Deep learning, Secular aesthetics, Digital cultural heritage

Introduction

Thangka, as a traditional Tibetan Buddhist art form, depicting various Buddha, mandalas, protector deities, ritual objects, and symbolic imagery, has a history of thousands of years and important historical, religious and cultural value [1]. Thangkas are rich in content and changeable in style. It has completed the organic combination of Tibetan Buddhist culture and art with unique artistic techniques. In 2009, UNESCO recognized thangka painting as an Intangible Cultural Heritage of Humanity, citing its cultural significance and importance in the preservation of Tibetan culture. In order to further protect and develop this cultural heritage, the digital research and protection of thangka images is of great significance.

Recently, a large number of studies have been carried out on the research and protection of thangka based on computer vision technology, including image recognition [2], detection [3], classification [4, 5], segmentation [6–8] and digital restoration[9–13]. It is shown that the

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computer vision technology has been widely, systematically and effectively applied and made rapid progress in the field of thangka digitization research. The digital analysis of thangkas faces great challenges. This depends on the quantity and quality of thangkas preserved, due to its long history, its raw materials are difficult to preserve, and thangkas have been damaged to varying degrees [14]. In addition, previous studies focused on the application of computer vision technology, lacking the combination with the cultural heritage and style of thangka art itself. Compared with the previous digital research on thangka images, face recognition technology [15], as the most researched topics in computer vision, has rarely been applied to the research on thangka images with a large number of Buddha faces. Therefore, face recognition technology can automatically and efficiently extract the facial features of Buddha statues, replacing the traditional method of visual observation based on experience, which is of great value for the digital research and protection of Buddha statues.

Face recognition is a method of biometric identification that uses automated methods to verify or identify a person based on physical characteristics [16], borned in the early seventies [17], the development of face recognition methods has greatly improved the accuracy from the traditional method relying on geometric features [18, 19] and machine learning technology [20–23] to the current deep learning methods based on models such as convolutional neural networks (cnns) [24] and residual networks (resnet) [25]. The traditional method is to extract image features first, and then use machine learning methods for recognition, this method not only has a complicated feature extraction process but also has poor generalization ability. Deep learning methods can be trained with very large data sets, thereby learning the best robust features to represent these data, achieving very high accuracy [26], but the model is complex and the recognition speed is slow. The core component of face recognition is the face recognition algorithm library, including opencv [27], Dlib [28], facenet [25], tensorflow [29], pytorch [30] and other algorithm libraries. As the most commonly used open source libraries for face recognition, Dlib and opencv both provide a series of computer vision tools, including face detection and recognition. The Dlib library is rich in content and provides high-quality libraries for machine learning, image processing, deep learning and face recognition [28]. The face recognition technology process mainly includes four parts, which are face image acquisition and preprocessing, face detection, face feature extraction and face recognition [31]. Face detection and feature point location are the first steps in face recognition. The input image is traversed through the window to determine the position and size of the face [32]. Face feature extraction, as the key to face recognition, describes the significant features of faces, and is currently dominated by deep learning methods [33]. Face recognition utilizes the extracted features and compares them with a database of known faces to identify faces, and facial feature comparison can be measured by Euclidean distance or cosine distance. Face recognition technology has a wide range of applications, including security surveillance [34–36], law enforcement [37–39], banking and finance [40, 41], healthcare [42, 43], education [44, 45], marketing and advertising [46]. However, due to the abstraction of portraits in historic paintings or sculptures, which are different from real human faces, the application of face recognition in the field of art history and cultural heritage research is very challenging. Only a few studies have applied face recognition to historical portrait identity and verification, Huber et al. Proposed a professional, likelihood-based fusion method for deep learning-based facial recognition of historical portraits [47], Ugail et al. Used deep learning human face recognition model effectively evaluates portraits in 16th-17th century oil paintings [48], and Andersen et al. Used facial emotion recognition algorithms to detect basic human emotions in British portrait art from 1500 to 1910 [49]. Most of these research objects are for realistic portraits like oil paintings, rather than abstract faces in religious art such as Buddha Statue, which are more difficult to identify. Combining face recognition technology and historical facial iconometric on the Tibetan canon of Buddha [50], Renoust et al. Proposed a method to obtain the facial figure line of Buddha statues, and used it for different classification tasks [51]. It can be seen that the research method of Buddha statues with face recognition technology formulated according to the historical facial iconometric is of great significance to cultural relics with special cultural value. Although the application of face recognition technology in Buddha statue art is challenging, some studies have shown that face recognition technology can be effectively used in the field of Buddha statue recognition and classification [51, 52]. However, previous studies on facial recognition of Buddha statues were mainly used in the field of classification of Buddha statues, and the facial features extracted by face recognition technology have not been further applied to the appreciation and evaluation of Buddha statue art.

In this research, based on the face recognition technology in the Dlib and the facial proportion standards of Canon of Iconometry for Buddhist Statues, the face digital evaluation method for thangka Buddha statues was proposed to study their historical evolution of facial

characteristics during the 11-19th centuries. In addition, explore the relationship between thangka Buddha face and human face in secular society according to facial features.

Materials and methods

Data acquisition

This study targets three classic types of Buddha statues in thangkas (108 pictures) during 11–19th century, which are Buddha, Bodhisattvas, and Buddhist goddesses. We summarized the details about the data set in Table 1. In addition, in order to compare and analyze secular faces with the faces of thangka Buddha statues. We collected 11 face pictures as secular face samples from Tibet, Han Chinese, Nepal, India, Inner Mongolia (Western Xia) and Kashmir.

Methods

Figure 1. Displays the framework of the proposed approach, which is made up of three parts. The first step is to recognize the face of the thangka Buddha statue and obtain 68 facial landmark points. The second

Table 1 Details of Buddha statues data set

Index	Thangka name	Century	Index	Thangka name	Century	Index	Thangka name	Century
1	Prajnaparamita	11th	37	Sakyamuni	16th	73	Ratnasambhava	18th
2	Avalokiteshvara	11th	38	Samantabhadra	16th	74	White Tara	18th
3	Avalokiteshvara	12th	39	Maitreya	16th	75	Sakyamuni	18th
4	Sakyamuni	12th	40	Mahakala	16th	76	Sakyamuni	18th
5	Bhaisajyaguru	12th	41	Avalokiteshvara	16th	77	Sakyamuni	18th
6	Avalokiteshvara	12th	42	Sakyamuni	16th	78	Sakyamuni	18th
7	Sakyamuni	12th	43	Sakyamuni	16th	79	Sakyamuni	18th
8	Dipankara	12th	44	Vairocana	16th	80	Maitreya	18th
9	Kunzang Gyalwa Dupa	12th	45	Sakyamuni	16th	81	Samantabhadra	18th
10	Vairocana	12th	46	Bhaisajyaguru	17th	82	Amitayus	18th
11	Green Tara	12th	47	White Tara	17th	83	Sakyamuni	18th
12	Sakyamuni	12th	48	White Tara	18th	84	Tathāgata	18th
13	Ratnasambhava	12th	49	Avalokiteshvara	18th	85	Kanakamun	18th
14	Dorje Sempa	12th	50	Buddha	18th	86	Sakyamuni	18th
15	Manjushri	12th	51	Sakyamuni	18th	87	Sakyamuni	18th
16	Dhyani Buddha	13th	52	Namgyalma	18th	88	Sakyamuni	18th
17	Sakyamuni	13th	53	Padmasambhava	18th	89	Vipasyin	18th
18	Sakyamuni	13th	54	Sakyamuni	18th	90	Sikhin	18th
19	Green Tara	13th	55	Four-Armed Avalokiteshvara	18th	91	Visvabhu	18th
20	Avalokitesvara	14th	56	Yellow Tara	18th	92	Krakucchanda	18th
21	Green Tara	14th	57	Amitayus	18th	93	Kanakamun	18th
22	Amitabha	14th	58	Buddha mother	18th	94	Kasyapa	18th
23	Sakyamuni	14th	59	Four-Armed Avalokiteshvara	18th	95	Sakyamuni	18th
24	Aksobhya	14th	60	Manjushri	18th	96	Amitayus	18th
25	Vairocana	14th	61	Manjushri	18th	97	Manjushri	18th
26	Aksobhya	14th	62	Dorje Sempa	18th	98	Sitatapatra	19th
27	Aksobhya	14th	63	Avalokiteshvara	18th	99	Four-Armed Avalokiteshvara	19th
28	Four-Armed Avalokiteshvara	14th	64	Chenrezig Ngesung Kundrol	18th	100	Manjushri	19th
29	Prajnaparamita	14th	65	Green Tara	18th	101	Samantabhadra	19th
30	Ratnasambhava	14th	66	White Tara	18th	102	White Tara	19th
31	Padmasambhava	15th	67	Tara	18th	103	Samantabhadra	19th
32	Sakyamuni	15th	68	Tara	18th	104	Manjushri	19th
33	Four-Armed Avalokiteshvara	15th	69	Namgyalma	18th	105	Sakyamuni	19th
34	Four-Armed Avalokiteshvara	15th	70	Four-Armed Avalokiteshvara	18th	106	Aksobhya	19th
35	Bodhisattva	15th	71	Namgyalma	18th	107	Amogha-pasha	19th
36	Ratnasambhava	15th	72	Samantabhadra	18th	108	Nagaraja	19th

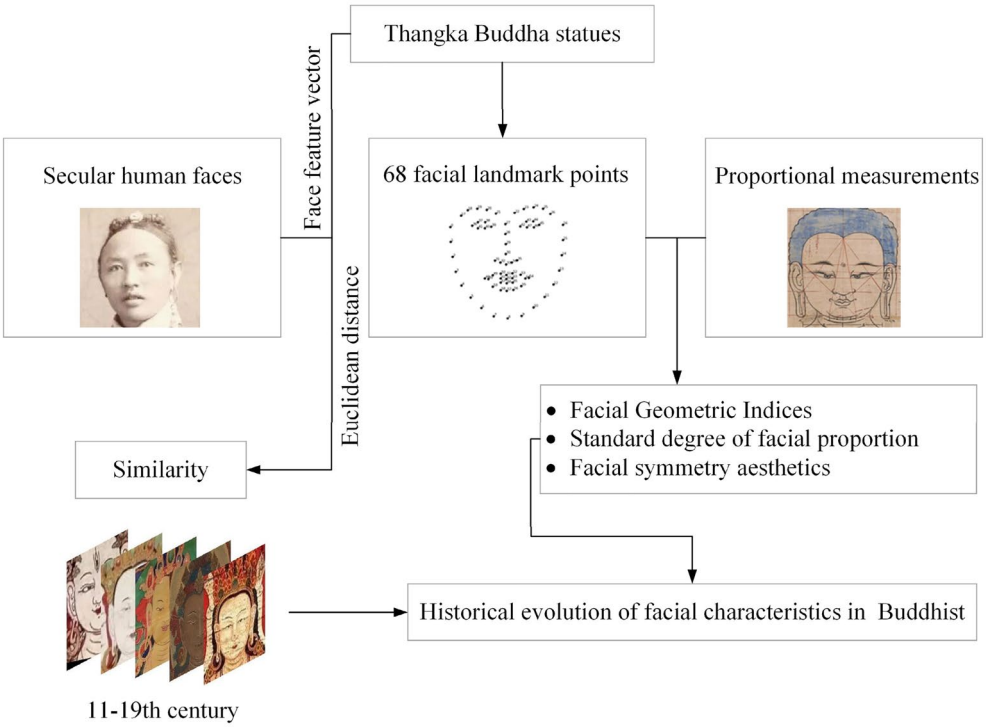

Fig. 1 Research method flow of face recognition of thangka Buddha statues and comparison with secular aesthetics

step is to combine the proportional measurements on Tibetan canon of Buddha to construct the facial feature evaluation indexs of the Buddha statue. The third step is to analyze the face of the thangka Buddha statue historical evolution of features, contrasting the relationship between Buddha statues and secular human faces.

Face recognition and feature extraction of Buddha statues

The Dlib facial recognition module can perform tasks such as face detection, feature point localization, face alignment, and face recognition by calling the frontal_face_detector() function, which is a face detector with HOG features. First, the image is converted to grayscale, and then the gradient direction and magnitude of each pixel are calculated to form a gradient histogram. Then, the gradient histogram is divided into several small blocks (cells), and the gradient direction of each small block is statistically analyzed to generate a feature vector. Finally, the feature vector is input into the classifier for classification to detect the location information of the face in the image. Then, we use the pre-trained shape model face_landmark_detection.py provided by the Dlib official website to detect the positions of 68 facial landmarks (Fig. 2) in the face. The face recognition model in Dlib used to extract facial features is a convolutional neural network with 128-dimensional output, which is trained based on the ResNet-34 as the underlying structure of its

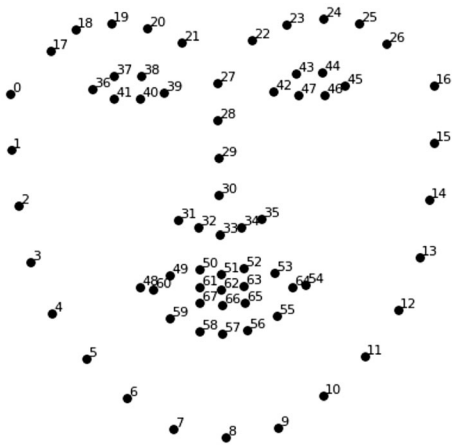

Fig. 2 68 Facial landmarks

face recognition network (Fig. 3). ResNet-34 is a 34-layer convolutional neural network whose main feature is the application of residual blocks to solve the problem of gradient disappearance. In the residual block, the skip connection is used to pass the input directly to the output, so that the model can more easily learn the changes of the input features. Based on ResNet-34, Dlib has modified it to make it suitable for face recognition tasks. Dlib adds a global average pooling layer to convert the output of the

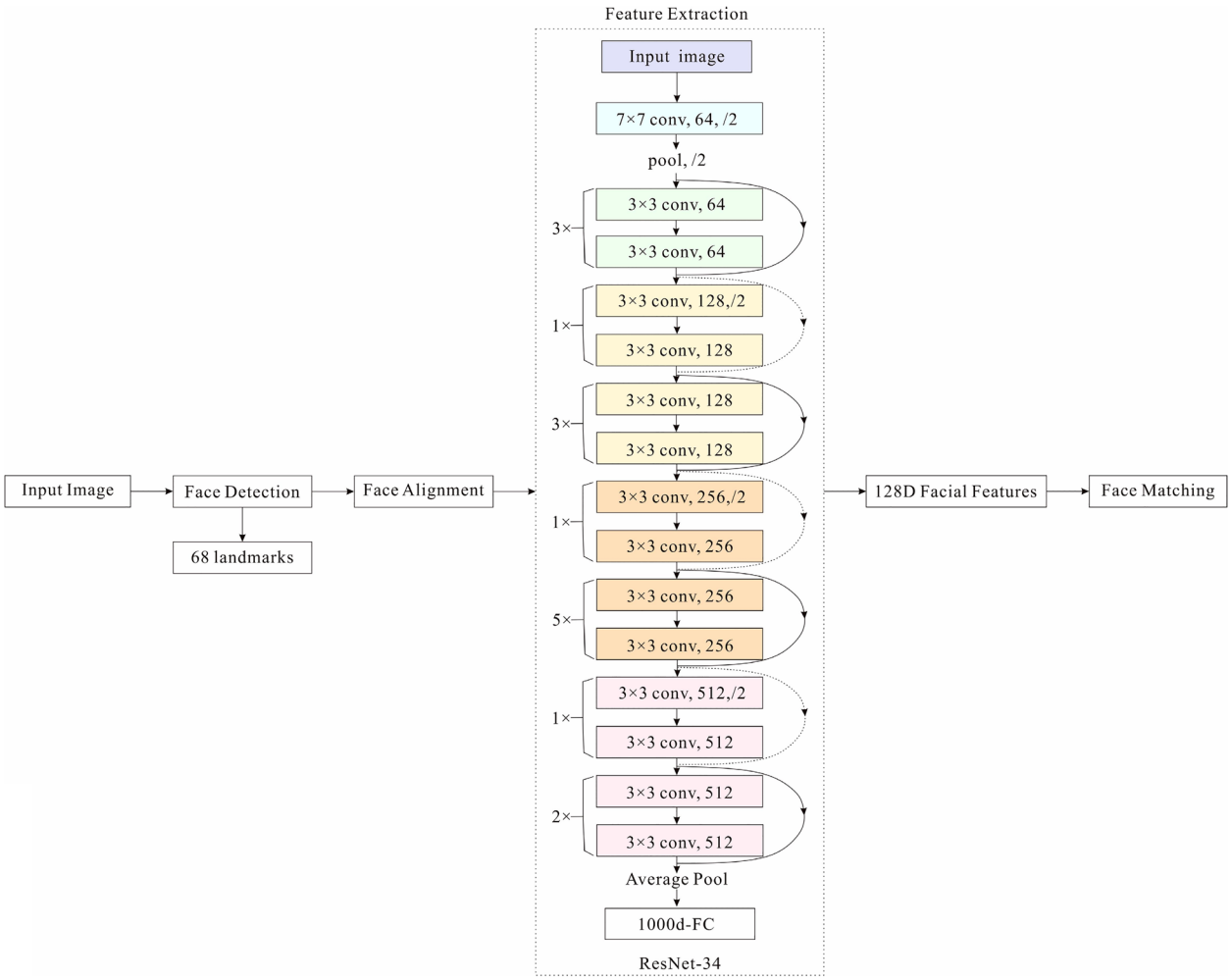

Fig. 3 The diagram of the face recognition process in Dlib

convolutional layer into a 128-dimensional feature vector. This feature vector is considered to be a unique representation of a face and can be used for face matching and recognition. After face recognition, the feature vectors of two facial images can be compared by calculating their Euclidean distance. If the distance is less than a certain threshold, the two faces are considered to belong to the same person. This work will be applied to a comparative analysis between the facial features of Tibetan thangka Buddhas and secular faces.

Construction of facial geometric indicators

The drawing of thangkas requires strict requirements, especially for the composition of the facial features of Buddha images, the basic unit (S) of facial measurement is one eye height as show in Fig. 4b. Thus, other parts proportions of the face are scaled based on this unit in thangka painting, these proportions are strictly followed and cannot be altered in the slightest: 1S for the distance from the eyebrow to upper eyelid, 2S for the distance from the eye to the bottom of the nose, 4S for the distance from the bottom of the nose to the chin, and 6S for the width of the face on either side as shown in Fig. 4b. According to Renoust et al. derived the Buddha iconometric proportions (Fig. 4a) in a Tibetan canon of Buddha facial regions based on 68 facial landmarks [51], we constructed eight geometric indices (A-H) based on the Buddhist canon of iconometry in 18 century [50], and other eight additional indices (I-P) regarding facial symmetry were extended. The above 16 facial geometric indices (A-P) together constitute the facial geometric indicators (FGI). This is a facial feature system proposed in this research for the characteristics of thangka Buddha statues. The computation of FGI indicators is based on the 68 feature point location data obtained through Dlib facial recognition technology. The calculation formula for FGI are presented in Table 2:

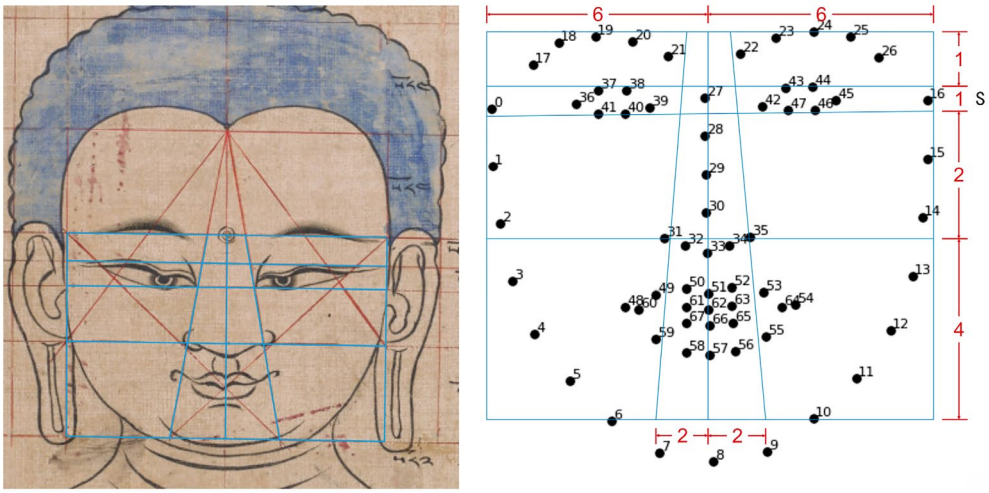

Fig. 4 The sketches of Buddha Face is shown in (**a**) and iconometric proportional guidelines defined from the 68 landmarks in (**b**), the basic unit S of facial measurement is one eye height

Evaluation of facial features of buddhist statues

The geometric proportions of the facial features of thangka Buddha statues have their own strict standards according to measurements of classical thangka Buddhist statues. These standards are very important for the formation of the theoretical system of Tibetan painting, and also reflect the technical level of thangka painters and their compliance with Buddhist laws. Therefore, based on the measurements of 18th century classical thangka Buddhist statues(Fig. 4a) in the Buddhist canon of iconometry[50], we established the index of standard degree of facial proportion(SDFP) to evaluate Buddhist statues face in thangka based on geometric facial feature indices A-H in Table 2. The closer the SDFP index is to 0, the more the facial drawing conforms to the classical facial proportion standard, the SDFP was described in Eq. (1).

$$\mathrm{SDFP} = \frac{\left|\frac{B}{A}-1\right| + \left|\frac{C}{A}-2\right| + \left|\frac{D}{A}-4\right| + \left|\frac{E}{A}-6\right| + \left|\frac{F}{A}-6\right| + \left|\frac{G}{A}-2\right| + \left|\frac{H}{A}-2\right|}{7} \tag{1}$$

Symmetry, as a fundamental design element in artistic aesthetics, can create a sense of neatness, harmony, and balance in a work, and is widely regarded as a symbol of beauty. Thangka is a mature artwork inherited from Tibetan Buddhism for thousands of years, which basically conforms to the objective aesthetic law of "symmetry". The symmetry of each part of the face of the Buddha statue is the basis of its beauty and solemnity, which reflects the characteristics of the history of thangka art development. Therefore, we take facial symmetry as indicator for evaluating the aesthetic beauty of Tangka Buddha statues' faces in this study. Based on all the geometric symmetry features indices E-P in Table 2 of the face, the index of facial symmetry aesthetics(FSA) to evaluate Buddhist statues face is constructed. The closer FSA is to 0, the higher the symmetry, indicating a stronger sense of facial symmetry beauty in the Buddha statue. The expression for FSA is as follows:

$$\mathrm{FSA} = \frac{\left|\frac{E}{F}-1\right| + \left|\frac{G}{H}-1\right| + \left|\frac{I}{J}-1\right| + \left|\frac{K}{L}-1\right| + \left|\frac{M}{N}-1\right| + \left|\frac{O}{P}-1\right|}{6} \tag{2}$$

Results

Evaluation facial normativity and aesthetics of the Buddha

By comparing and analyzing the geometric characteristic indices of the facial features of 13 classic Buddha statues, as shown in Fig. 5, the measured values of indices A, G, H, O, and P corresponding to the width of the eyes, chin, and nose in the Buddha statues exhibit convergence, indicating that the depiction of these facial features in these Buddha statues is more standardized and has a strong normativity. However, the measured values of indices C, D, E, F, I, and J corresponding to the height between the eyes-nose-chin, face width, and eyebrow width of the Buddha statues exhibit significant differences and

Table 2 Facial geometric indicators(FGI) of Buddha

FGI	Code	Formula	Legend
Eye height	A	$S = \frac{d41_y - d37_y + d40_y - d38_y + d47_y - d43_y + d46_y - d44_y}{4}$	
Eyebrow to upper eyelid	B	$S = \frac{d37_y - d17_y + d38_y - d21_y + d43_y - d22_y + d44_y - d26_y}{4}$	
Eye to nose bottom	C	$2S = \frac{2(d31_y + d35_y) - (d40_y + d41_y + d46_y + d47_y)}{4}$	
Nose bottom to chin	D	$4S = \frac{(d6_y + d10_y) - (d31_y + d35_y)}{2}$	
Right cheek width	E	$6S = d16_x - d8_x$	
Left cheek width	F	$6S = d8_x - d0_x$	
Right chin width	G	$2S = d10_x - d8_x$	
Left chin width	H	$2S = d8_x - d6_x$	
Left eyebrow width	I	$d21_x - d17_x$	
Right eyebrow width	J	$d26_x - d22_x$	
Left eye width	K	$d39_x - d36_x$	
Right eye width	L	$d45_x - d42_x$	
Left mouth width	M	$d51_x - d48_x$	
Right mouth width	N	$d54_x - d51_x$	
Left nose width	O	$d33_x - d31_x$	
Right nose width	P	$d35_x - d33_x$	

"x" and "y" represent the horizontal and vertical coordinates of a feature point, and "dn" represents the nth feature point on a face

high dispersion, indicating that the depiction of these facial features in these Buddha statues is less standardized and has a more diverse style in these areas. Overall, the study found that the spectral lines of the 16 geometric feature indices of the 13 Buddha facial images were consistent. This consistency represents the existence of

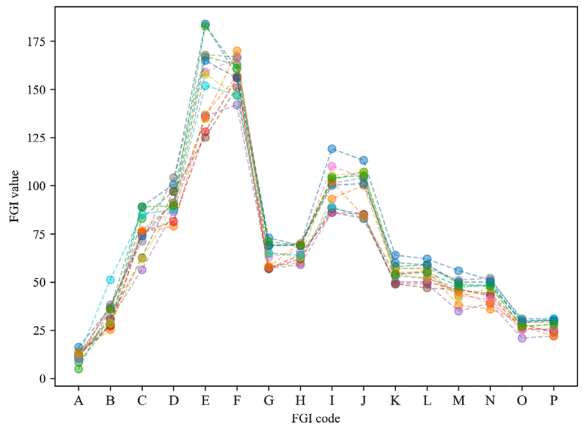

Fig. 5 Facial geometry measurements of classic Buddha statues, the facial geometric indices A-P (X-axis) are codes of FGI in Table 2, the FGI value (Y-axis) is measured value of indices A-P, each colored line represents the FGI measurement result of a corresponding Buddha face sample

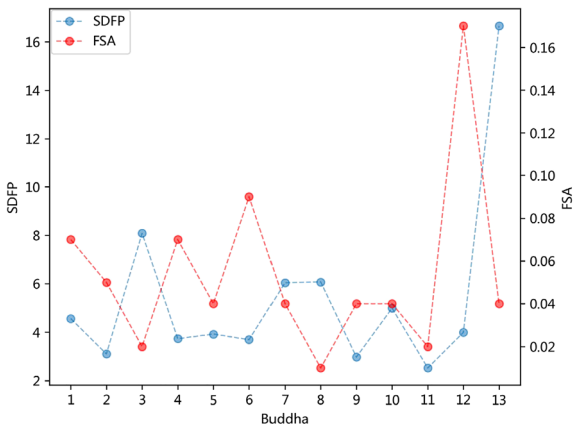

Fig. 6 The SDFP and FSA values of 1–13 Buddha statues face in Fig. 7

a Buddha measurement system used in the depiction of Buddha facial features. The spectral lines have common directional and fluctuation characteristics, representing well the facial geometric feature of Buddha statues. There are subtle differences between the facial geometric feature curves of different Tangka Buddha statues, and the results show that the 16 geometric feature indices constructed for the facial features of Buddha statues can well represent the structural features of Buddha face and can also distinguish Buddha statues well from the differences in curves characteristics.

Based on the geometric feature indicators of the Buddha's facial features, we have constructed two evaluation indicators for Tangka Buddha images: the standardized proportionality indicator SDFP and the symmetry aesthetic indicator FSA. By evaluating the facial features of 13 Tangka Buddha statues according to the classical facial proportion standards of the 18th century, we found that SDFP varies greatly among the facial features of the Buddha statues, with Buddha images 3, 7, 8, and 13 having relatively insufficient standardization in facial proportionality (Fig. 6). In particular, Buddha image 13 has a lower standardization due to its small eye height, which, as the basic unit, causes the geometric indicators B-H to be imbalanced, resulting in a higher SDFP value and non-standard evaluation results. The most standardized facial proportion for Buddha statues are 9 and 11, with SDFP values of 2.97 and 2.52 respectively. This indicates that the artist followed the standards for classic measurements closely and was strict with controlling the facial proportions when painting thangka. It's worth noting that although Buddha statue number 1 was completed in the 14th century, earlier than other Tangka paintings from the 18th century, its facial proportions are standardized, with a SDFP value of 4.56, reflecting the maturity of the artist's painting skills. SDFP, as an indicator of whether the facial proportions of a Tangka Buddha statue are standardized, can not only distinguish the level of standardization of the statue's painting but also reflect the painter's painting skills. The evaluation of the facial proportions of Buddha statues using SDFP is specific and efficient, providing digital and effective support for the identification and protection of Tangka cultural heritage.

By comparing the symmetrical aesthetics values FSA of 13 Buddhist statues as shown in Figs. 6 and 7, we found that the FSA values of statues number 6 and 12 were lower, at 0.09 and 0.17, respectively. This indicates that their facial symmetry aesthetics are poorer compared to other statues. The reason for the lower symmetry aesthetics of statue number 6 is due to the large difference in the left and right width of the face and chin. Statue number 12 has the worst symmetry aesthetics due to even greater differences in the left and right width of the face, chin, and eyebrows. Although the proportions of the facial features in this statue are well controlled, the symmetry aesthetics are poor. Overall, the painter's skills are not mature enough, and there are flaws in the aesthetics. The Buddhist statues with high symmetry aesthetic value are the 3rd, 8th, and 11th statues, with FSA values of 0.02, 0.01, and 0.02, respectively, all very close to 0, indicating their extremely high symmetry aesthetic value. The symmetrical beauty of the statues enhances the perception of the Buddha's wisdom and compassion. Artists often use symmetry to express their aesthetic views and artistic style, further enhancing their individuality and stylistic characteristics. This also reflects the skillful grasp of aesthetics and artistic style by the three Tangka artists mentioned above. The 11th statue possesses both standard facial proportions and high symmetry aesthetic value,

Fig. 7 1–13 Tangka Buddhist statue facial images

reflecting the mature level and profound understanding of Buddhist doctrine possessed by the Tangka artist who created it. Overall, the FSA values of all the statues' facial symmetry aesthetic index are close to 0, indicating a strong sense of symmetry beauty. The FSA value can reveal the subtle facial asymmetry of the Buddhist statue, and is sensitive to the beauty of the statue's face, allowing for an efficient and precise evaluation of the symmetry aesthetic value of the statue's face, while also identifying the areas where symmetry is lacking. This provides reliable data support for the assessment of the Tangka artist's skills and the aesthetic value of their Buddhist statues.

The historical evolution of facial characteristics in Tangka Buddhist statue

According to the classic standard proportions for the faces of Buddha, Bodhisattva, and Buddhist goddesses in the Canon of Iconometry for Buddhist Statues from 18 century as shown in Fig. 8, we collected 108 facial images of thangka paintings from the 11th to the 19th centuries. We applied facial recognition and feature point extraction technology to these images, calculated facial geometric indicators, and obtained SDFP and FSA values for each facial image of Buddha. These values were used to evaluate the standardization and aesthetics of the facial proportions in thangka paintings. We established a historical time series of thangka facial images and analyzed the historical evolution of the facial features of Buddha.

By calculating the geometric features of the facial characteristics of Buddhist statues spanning 9 centuries, we obtained the FGI values of Tangka Buddhist statues over the past thousand years. Figure 9 shows a comparison of the 16 geometric indices of each century's Buddhist statues, and the results indicate that the fluctuation pattern of the facial geometric indicators of these 108 Tangka Buddhist statues is basically the same, reflecting the existence of a common standard for the proportions of Tangka Buddhist faces. At the same time, due to differences in the types of statues and painting styles, there are local differences in the facial geometric feature curves of the statues, caused by facial geometric indices E, F, I, and J, which refer to the width of face and eyebrows. This shows that the width of the face and eyebrows are key distinguishing features in the depiction of different Tangka Buddhist statues.

In the 11th century, two Buddha statues had similar geometric facial features curves (Fig. 9a), and the Euclidean distance between their feature vectors was 0.53.

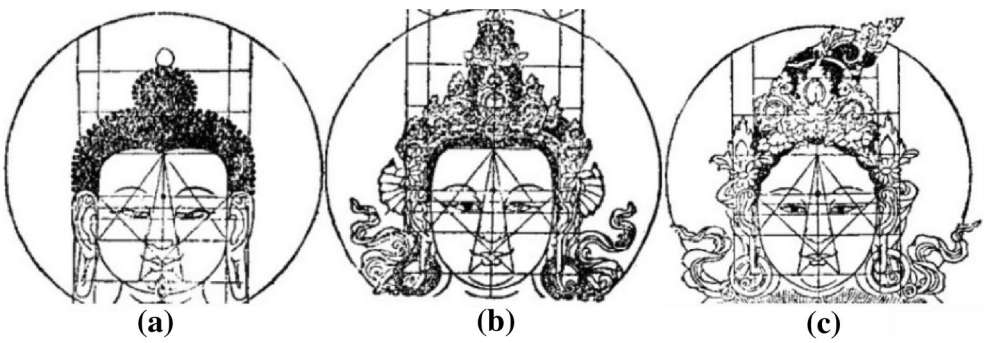

Fig. 8 The standard proportions for the faces of **a** Buddha, **b** Bodhisattva, and **c** Buddhist goddesses

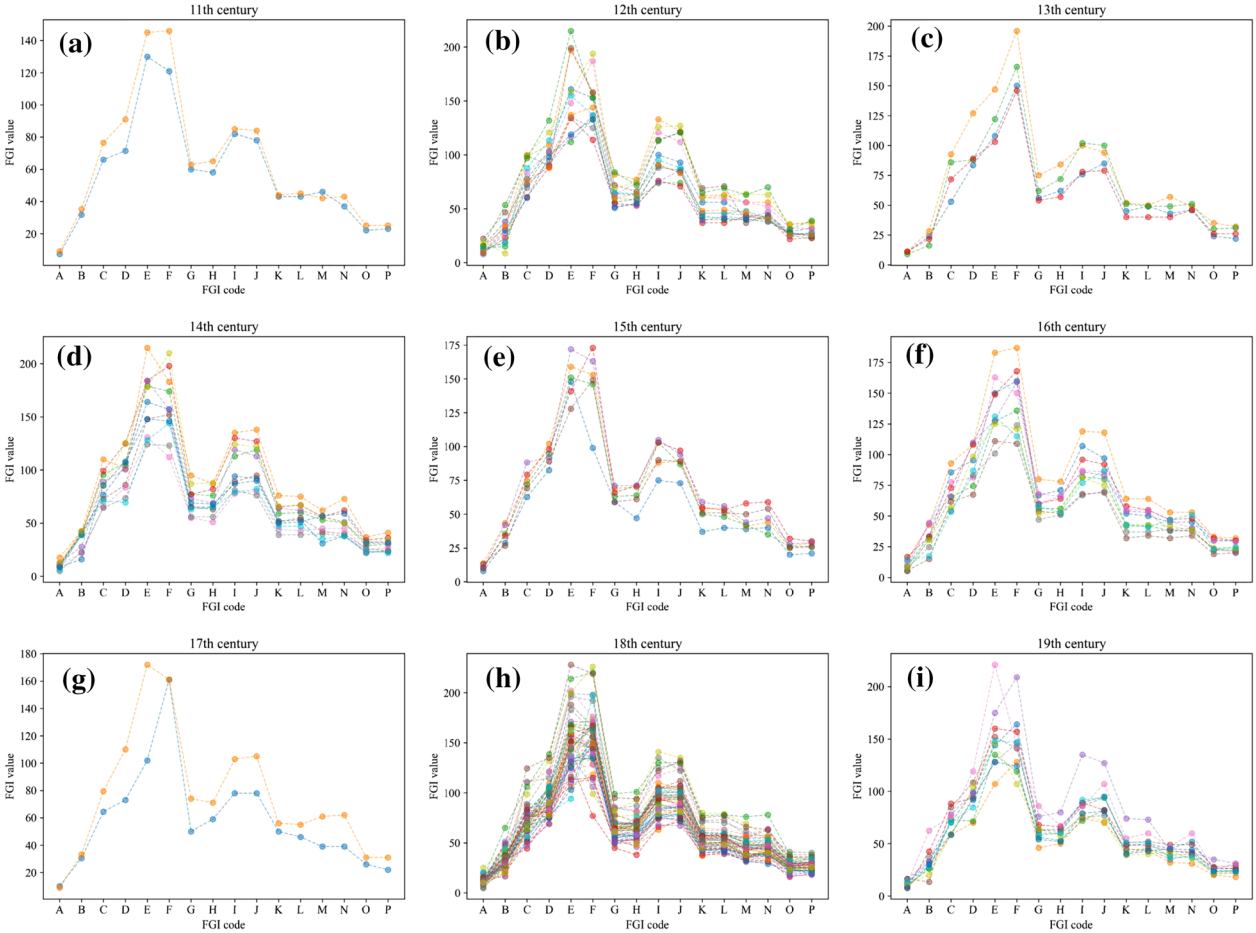

Fig. 9 The Facial geometric indicators(FGI) value of Tangka Buddhist statues over the 11–19 century, **a–i** correspond to the 11th–19th centuries respectively, the facial geometric indices A-P (X-axis) are codes of FGI in Table 2, the FGI value (Y-axis) is measured value of indices A-P, each colored line represents the FGI measurement result of a corresponding Buddha face sample

For an abstract face like Buddha, a small Euclidean distance between them represents a high degree of similarity. Based on the comparison results of SDFP and FSA as mentioned in Fig. 10a and b, the aesthetic symmetry FSA of the Buddha's facial features in this period was the best during 9 centuries. However, because it is the oldest period, it deviates the most from the classic proportion standards established in the 18th century. There were no strict measurement standards for drawing Buddha statues, but the images were harmonious and beautiful, and the aesthetic sense of symmetry was strong during this period.

In the 12th century, there were many collections of Buddhist statues, and the geometric features of their faces showed consistent wave-like patterns as shown in Fig. 9b. The facial proportions of these statues were relatively uniform, with a SDFP value of 3.93 as shown in Fig. 10a, which closely adhered to the classic standards of facial proportions. However, compared with before, there was a decrease in symmetry and aesthetic beauty during this period, with a FSA value of 0.08 as shown in Fig. 10b, resulting in a decrease of overall harmony in the Buddhist statues images.

In the 13th century, there was limited data collection, and the FGI values of Buddha statues showed convergence in their fluctuation curves as shown in Fig. 9c. However, the facial proportions of Buddha statues differed greatly from the classic standard proportions, with longitudinal FGI indicators B, C, and D (i.e. The proportions between the eyebrow and upper eye, eye and nose bottom, nose bottom and chin position) being the main contributors to this difference as shown in Fig. 9c. The longitudinal facial proportions were significantly different from the classic proportions of 1:2:4, possibly due to the influence of the social cultural context and aesthetics of the time. The values of SDFP (5.08) and FSA (0.1) both increased compared with previous period (Figs. 9b and 10a), indicating that the proportion standard and

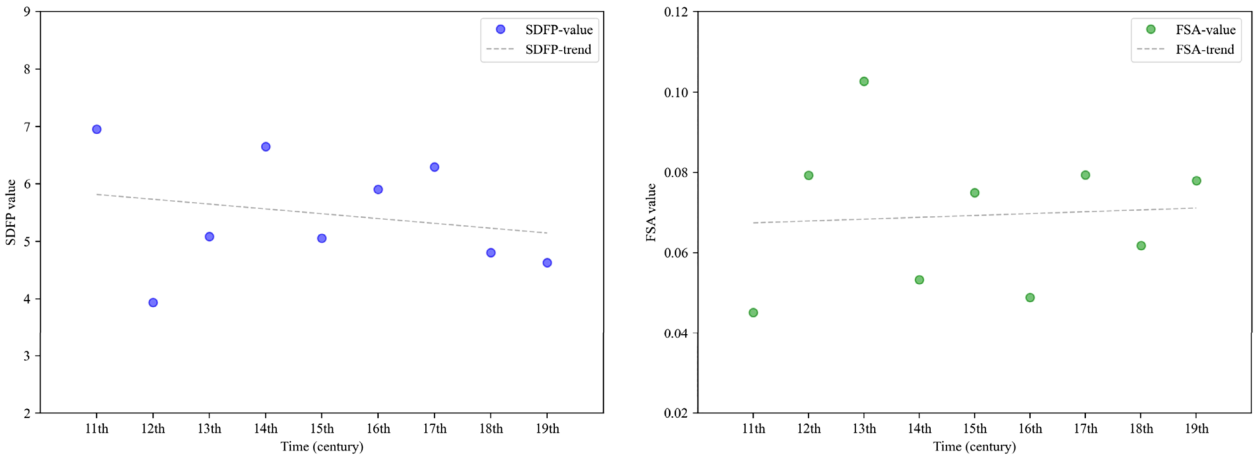

Fig. 10 The values and their trends of **a** SDFP and **b** FSA obtained on thangka Buddhist statues data set during the 11–19 century

symmetry of Buddha statues in this period decreased, the facial features of Buddha statues were more differentiated, and the drawing styles of thangka were diversified.

In the 14th century, there were differences in the FGI of thangka Buddhist images, indicating a diverse range of facial styles. However, the curves of the facial features were consistent, indicating that there were standards for facial proportions during this period as shown in Fig. 9d. Nevertheless, the standards for facial proportions during this time differed significantly from the classic facial proportions of the 18th century, and the SDFP (6.65) value was much higher than 0 (Fig. 10a), indicating that the facial proportions of the Buddha images during this period did not adhere closely to the 18th century classical standards. Compared with the previous period, the facial features of Buddha statues in this century are less standardized, which reflects that the painting styles of thangka Buddha statues' faces are more diverse at this time. The FSA index of symmetry aesthetic was 0.05 as shown in Fig. 10b, very close to 0, indicating that the thangka Buddhist images during this period were exquisitely drawn and had harmonious facial features.

In the 15th century, the facial geometry curves of Tangka Buddhist images were relatively close to each other as shown in Fig. 9e, with a common standard of facial geometric proportions. Using the classic facial proportion standards of the 18th century to evaluate the Tangka Buddhist images of this period, a SDFP value of 5.05 was obtained (Fig. 10a), which is closer to a value of 0. This indicates that during this period, Tangka Buddhist images had begun to approach the classic facial proportions in their depiction. It shows that the facial painting skills of thangka Buddha statues in this century has a great influence on the Tibetan Buddhist art formation of later generations. Meanwhile, the FSA value of the symmetry of the facial features of the Buddhist images was 0.07 as shown in Fig. 10b, indicating a high level of symmetry aesthetic appeal. Overall, the evaluation of the facial features of the Tangka Buddhist images of the 15th century was good, approaching the classic facial proportions, and possessing a high level of symmetry aesthetic appeal, indicating a high level of skill and maturity in the style of the painters.

In the 16th century, there were differences in the FGI curve of Tibetan thangka Buddha images as shown in Fig. 9f. Using the classic proportion standards from the 18th century to evaluate the Buddha images from the 16th century, a SDFP value of 5.9 was obtained as shown in Fig. 10a, which is far from the standard SDFP value of 0. This indicates that the facial proportions of the Buddha images in this century were significantly different from the classic standard proportions. Compared with the 15th century, the facial proportions of Buddha statues were once again reduced in standard during this period, which means that the thangka painting styles of this period were quite different. The aesthetic value of symmetry, FSA, was 0.05 as shown in Fig. 10b, which is extremely close to the standard FSA value of 0. This means that the pursuit of symmetrical aesthetics in the face painting of thangka Buddha statues in this century has reached the extreme and these thangka works emphasized the harmony and beauty of facial features and pursued the beauty and serenity of facial expressions through the high symmetry of facial features.

The geometric characteristics of the faces in two White Tara statues from the 17th century differ significantly in terms of their curve patterns as shown in Fig. 9g, and their SDFP average value (6.29) deviate significantly

from the standard value of 0 as shown in Fig. 10a. This means that the facial proportions of thangka Buddha statues in this century are not standardized enough, and they are quite different from the classic facial proportions in the Canon of Iconometry for Buddhist Statues of the 18th century. Compared with the 16th century, both the standard of facial proportions (SDFP) and the beauty of symmetry (FSA average value is 0.08 as shown in Fig. 10b) have weakened. The thangka painting skills of this period did not follow the classic standards of the facial proportions of Buddha statues, and did not have a profound impact on the later stages of thangka painting art.

In the 18th century, there were a large number of thangkas, and FGI of the Buddha statues had relatively small differences in their curves (Fig. 9h). The fluctuation characteristics of the geometric feature curves representing the faces of the Buddha statues tended to be consistent, indicating the maturity of the proportional standards for the faces of the Buddha statues at that time. By using the classical facial proportion standards to evaluate the thangka data, the SDFP value was 4.8 as shown in Fig. 10a, which was closer to the standard value of 0. This indicates that the drawing of the faces of the Buddha statues strictly followed the classical proportion standards during this period. The drawing technique of the faces of thangka Buddha statues in this century has strict and uniform standards, and the SDFP values of the faces of different thangka Buddha statues are highly consistent. The aesthetic index of symmetry, FSA value was 0.06 (Fig. 10b), which was close to the standard value of 0, indicating that the symmetry of the faces of the Buddha statues was extremely high, and the beauty was stronger, showing the maturity and prosperity of thangka painting during this period.

In the 19th century, the curves of the FGI in Tangka paintings inherited the characteristics of the 18th century. The differences between the Buddha statues were relatively small, and the fluctuations of FGI curves were consistent. The SDFP value was 4.6 as shown in Fig. 10a, which was closer to the standard value of 0. This means that the Tangka paintings of this period further strengthened the norms of the Canon of Iconometry for Buddhist Statues and reached the highest historical level.

From the 11th to the 19th century, the SDFP value showed a decreasing trend as shown in Fig. 10a, gradually approaching the standard value of 0. The painting of Buddha faces became more and more standardized, and the classical proportion standards in "Canon of Iconometry for Buddhist Statues" continuously strengthened its regulations on Tangka Buddha painting. In the 18th and 19th centuries, this standardization effect reached its highest historical intensity. The value of FSA (Fig. 10b), which represents the aesthetic symmetry, remained stable, in line with the aesthetic characteristic of pursuing symmetry and smoothness in Tangka painting. However, the development of geometric proportion standards for Buddha face painting was a tortuous and repetitive process. With the changes in historical and social environments, the value of SDFP approached the standard norm value 0 during the heyday of Tibetan art, and moved away from the standard norm during turbulent periods, with an increasing difference in FGI curves between the Buddha faces. This proves that the geometric indicators of facial recognition technology derived from Dlib face recognition technology and the Buddha face feature evaluation indicators SDFP and FSA that we constructed can accurately capture the differences in facial features between Buddha faces and the standard level and aesthetic strength of Tangka Buddha face painting.

Comparative between thangka Buddhist and secular human faces

We have selected a Buddhist statues painting from the ancient kingdom of Guge in Tibet as our comparative Tangka data in the 11th century. And used facial data of indigenous people from Tibet (Guge Kingdom), Nepal, and Kashmir as secular facial data for this thangka because it incorporates artistic elements from all three regions. After facial recognition and feature extraction, it was found that this Tangka Buddha statue from the 11th century has the smallest Euclidean distance of 0.64 with the facial features of people from Ali region in Tibet as shown in Fig. 11. The overall facial features of the two are most similar, indicating that the facial aesthetics of this Tangka Buddha statue are based on secular facial features of the Guge Kingdom, rather than a pure Kashmiri artistic style. At the same time, the Euclidean distance

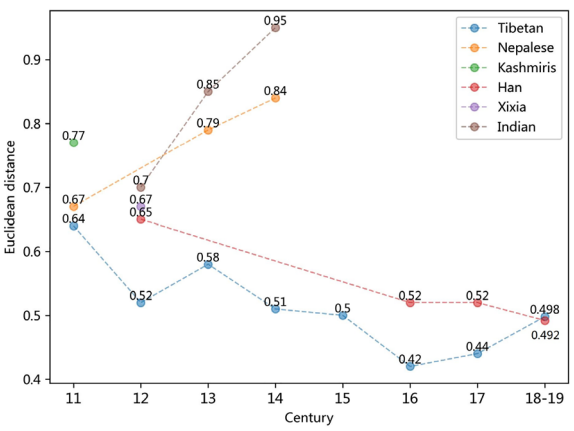

Fig. 11 Euclidean distance between thangka Buddhist and secular human faces over the 11–19 century

between the facial features of the Buddha statue and the Nepalese people during this period is 0.67, indicating a close relationship with secular facial features in Nepal.

Most of the 12th century thangka paintings were unearthed from Heishui City in Inner Mongolia, which have been proven to be from the Western Xia period of 1227. During this period, the painting style of the Western Xia dynasty integrated Han and Tibetan artistic styles. The figures depicted in these paintings are similar to the Pala style of contemporary India. In order to explore the secular roots of the aesthetic style of the facial features in these thangka paintings, this study selected one Buddhist statues painting of them and used feature vector Euclidean distance analysis to compare the facial features with the indigenous people of Tibetans, Han Chinese, the Western Xia region (present-day Ejinaqi, Inner Mongolia) and India. The results showed that the facial features of Buddha face in this thangka painting are most similar to tibetan face, with an Euclidean distance value of 0.52 as shown in Fig. 11. The facial aesthetic style of these thangka was mainly Tibetan artistic styles. The secular aesthetic preferences of the faces in Tibet corresponded strongly with the thangka paintings produced in Heishui City during this period.

In the 13th century, the Pala style in Northeast India integrated local Tibetan aesthetic interests and formed the "Gandenba" art. It became the mainstream art style of Tibetan Buddhism in the 13th century and had a great influence on later art styles. At the same time, Nepalese art was mainly based on Pala art and integrated Nepalese and Tibetan ethnic aesthetics, becoming the mainstream art style in Tibet after "Gandenba". To explore the aesthetic roots of the mainstream art of Buddha's face during this period, we selected the representative work of the "Gandenba" style, the Tangka of Shakyamuni Buddha's Sermon, as well as the facial images of indigenous people from Northeast India, Tibet, and Nepal. Through facial recognition technology, we calculated the Euclidean distance between the Tangka Buddha's face and the feature vectors of different regional faces. The results showed that the facial features of the "Gandenba" style Buddha were closer to the local Tibetan face, with a Euclidean distance value of 0.58 as shown in Fig. 11, which was the lowest among the three control groups. This represents a distinct Tibetan ethnic aesthetic characteristic in the Buddha's face during this period, and the aesthetic of the Tangka Buddha's face during this period has a close correlation with the secular faces of the Tibetan region.

In the 14th century, the Sakya sect dominated the Tibetan Buddhist art style. We have chosen the Tangka of the immovable Buddha, which belongs to the Sakya sect and continues the Palas style. The Pala art style originated in East India, was transmitted to Tibet through Nepal, and combined with Tibetan local aesthetics and craftsmanship. In order to distinguish the secular roots of the facial aesthetics of Tangka Buddha during this period, we have selected the faces images of indigenous people in India, Nepal, and Tibet and conducted a Euclidean distance analysis between the facial features of this Tangka Buddha and people face. The results are the same as in the 13th century. The facial aesthetics of Sakya Tangka Buddha are closely related to the secular faces of Tibetans. The facial features preferred by local ethnic groups have deeply influenced the aesthetic characteristics of Tangka Buddha's facial features.

In the 15th century, there was a significant change in Tibetan thangka art. The dominance of foreign art from India, Nepal, Kashmir, and other places came to an end, and local Tibetan art created the Mianning, Qinzhi, Gama Gazi, Jiangzi, and o'er schools of art, among which the Mianning school was the most influential local art school. We selected a 15th-century old Mianning-style four-armed Avalokitesvara thangka, whose facial features have a distinct Tibetan expression and charm, and therefore chose the indigenous people's faces in Mianning (now Shannan, Tibet) as a secular contrast to the Buddha's face, and calculated the Euclidean distance between the two faces, resulting in a value of 0.53 as shown in Fig. 11. The aesthetic of this Mianning-style thangka Buddha's face has a good contrast relationship with the local secular faces in Tibet during this period, indicating that the local characteristics of thangka were very distinct.

In the 16th century, Tibetan Buddhist thangka paintings incorporated Han Chinese style artistic features and composition forms, combining them with Tibetan art. To explore the secular origins of the facial aesthetics of tangka Buddha statues during this period, this study selected a Maitreya Bodhisattva tangka from the 16th century, which not only represents a high level of early Tibetan painting, but also has been influenced by Han Chinese style painting. We used features of Tibetan and China indigenous people's faces to calculate Euclidean distance between the facial features of the tangka Buddha and two human faces. The results showed that the Euclidean distance between the tangka and Tibetan faces was 0.42, while that between the tangka and Han faces was 0.52 as shown in Fig. 11. Although the creation of tangkas during this period was influenced by Han Chinese style painting in facial depiction, the main source of facial aesthetic was still derived from the secular faces of Tibetans. There is little data available for the 17th century, but the facial aesthetics of this period are still primarily influenced by Tibetan faces and secondarily by Han Chinese faces, similar to those in the 16th century.

In the 18th and 19th centuries, the production of thangka paintings in Tibet was abundant, with rich

content and mature and comprehensive techniques, which was a prosperous period for Tibetan thangka art. Tibetan Buddhist thangka art received support from the Qing government and absorbed and integrated Chinese techniques while maintaining its local artistic characteristics. This study selected a thangka painting of a Buddhist mother from the 18th century and compared it with the faces of indigenous people from Tibet and China. The Euclidean distance between the thangka image and human faces was calculated, and the results showed that the Euclidean distance between the face of the Buddhist mother and the Tibetan face was 0.498, while that between the face of the Buddhist mother and the Chinese face was 0.492 as shown in Fig. 11. This indicates that during this period, Tibetan Buddhist art was deeply influenced by Han Chinese styles, resulting in thangka facial features that were more similar to the secular faces of Han people, and a profound fusion of Tibetan and Chinese aesthetics.

From the 11th to the 19th century, the secular aesthetic sources of the facial features of Tangka Buddha images were mainly based on the faces of local Tibetans. In the 11th century, Tangka Buddha images were not only correlated with the faces of local Tibetans, but also had strong connections with Nepalese faces. By the 12th century, the secular aesthetic preference for local Tibetan faces had deepened, further making Tibetan faces the main reference for depicting Buddha image faces. At the same time, Tangka Buddha images also incorporated facial features from the Western Xia, Chinese and Indian ethnicities, which was a period of blending diverse secular aesthetics. From the 13th to the 15th century, the pursuit of localization in the facial aesthetics of Tangka Buddha images further deepened, and the influence of Nepalese and Indian artistic styles gradually weakened. Tangka Buddha image faces no longer had exotic facial aesthetics. In the 16th and 17th centuries, Tangka Buddha images were influenced by Han Chinese artistic styles and blended with Tibetan art. By the 18th and 19th centuries, this blending relationship was further strengthened, and the secular aesthetic elements of Tibetan and Han Chinese faces in Buddha image faces were almost equal, achieving a deep blending of ethnic facial aesthetics in Tangka Buddha image facial aesthetics.

Overall, by comparing the facial features of Tangka Buddhist images with those of secular faces and calculating the Euclidean distance between them, we can effectively determine the sources of facial aesthetics in Tangka Buddhist images. Additionally, distinguishing the strength of the correlation between different secular faces and Tangka Buddhist images can serve as a basic tool for the appreciation and study of Tangka cultural heritage. This has an important supporting role in sorting out the evolutionary process of the secular sources of facial aesthetics in Tangka Buddhist images. Applying facial recognition technology to the protection, appreciation, and research of cultural heritage is of great practical significance for the preservation and inheritance of such cultural heritage.

Discussion

Face recognition technology can be effectively applied to face recognition of thangka Buddha statues, and the geometric proportions of Buddha statues constructed based on facial landmark points can accurately reflect the facial structure characteristics of thangka Buddha statues in a specific period. The evolution of thangka Buddha statue faces is a tortuous but constantly standardized process. During this process, the secular reference of thangka for face painting mainly comes from local Tibetan faces. In the later stages of thangka evolution during the 18-19th centuries, the faces of Buddha statues showed the aesthetic integration of Tibetan and Han Chinese.

This is an effective attempt to apply face recognition technology to the study of thangka Buddha statues, the standard degree of facial proportions and symmetrical beauty evaluation indicators of Buddha statues constructed by combining face recognition technology with metrics can effectively and accurately evaluate the facial features of Buddha statues, which provides a new perspective for the study of thangka cultural heritage. This method can use face recognition technology to capture difficult-to-recognize details, and at the same time facilitates an intuitive understanding of its religious and cultural significance. The computer vision technology has broad application prospects in the field of cultural heritage, and has been applied in the restoration of thangka protection work [2–13]. However, computer vision technology faces some challenges, such as light, angle, color and resolution, which affect the accuracy of image recognition [53], the recognition of thangka Buddha statues in this study also encountered these problems. Some thangka images were of poor quality, which made face recognition difficult, so the number of thangkas that could be recognized by faces was reduced, we believe that this requires more efficient and accurate image processing and computer vision techniques to solve.

In the field of Buddha statues research, a small number of experts subjectively identify the style of these classic works based on experience, and a few studies combine the classic Buddha statue measurement method with face recognition technology to determine the facial proportions of the image Buddha statues, Renoust et al. Proposed a method based on the 68 facial landmarks are used to obtain the facial figure fingering line of the Buddha statue, and use it for the classification task of

different Buddha statues [51]. This proves that using historic iconometry to determine the facial proportions of an image Buddha is a viable way. It allows us to understand how thangka artists from different eras and geographical locations proportionally distributed key facial areas when depicting Buddha statues. This is consistent with the point of view of this study, the application of the Buddha statue iconometric guidelines is very simple and easy to understand for the study of thangka art. The difference is that this study uses the classic iconometric guidelines of Buddha statues to construct the index SDFP for evaluating the standard of facial proportions of Buddha statues. The results show that SDFP can effectively evaluate the standard degree of drawing thangka Buddha statues.

In addition, the secular faces that best correspond to thangka Buddha statues are mainly from Tibet, due to the abstraction of Buddha statues, there is almost no research on the relationship between Buddha statues and secular faces. By calculating the Euclidean distance between thangka Buddha statues and secular face feature vectors, there are indeed different intensities of relationships between Buddha statues and human faces in various regions. This is a preliminary attempt, in order to prove the effectiveness of this method of analyzing the relationship between Buddha statues and faces, we will need further experiments to collect more rigorously verified secular face data and high-quality thangka Buddha statue data from regions in special periods.

Conclusions

This study recognize the face of thangka Buddha statues through the Dlib machine learning library, and finds that face recognition technology can effectively and accurately obtain the facial features of Buddha statues. We combined the 68 facial landmarks of Buddha statues with the proportional measurements on a Tibetan canon of Buddha to construct indicators SDFP(standard degree of facial proportion) and FSA(facial symmetry aesthetics) for evaluating the facial features of Buddha statues. The results show that SDFP and FSA can efficiently and accurately evaluate the facial features of thangka Buddha statues automatically, and reflect the differences between the facial details of Buddha statues. The historical evolution of thangka Buddha statues is a tortuous process, but the drawing skills are constantly standardized, and the Buddha statues have always maintained a high degree of symmetrical beauty. The results of comparative analysis of thangka Buddha statues and secular faces show that the secular origin of the facial features of Buddha statues is mainly Tibetan local faces. In the 18th and 19th centuries, the absorption of Han Chinese facial features appeared, reflecting the aesthetic fusion of Tibetan and Chinese art. Future research still needs more quantity and high-quality data of thangka Buddha statues to support this research method and reduce the dependence of this method on data.

Author contributions
Software, validation, visualization, writing, YY; methodology, resources, data curation, conceptualization, supervision, FF All authors have read and agreed to the published version of the manuscript.

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