Heritage Science

RESEARCH ARTICLE

Open Access

Measurement and analysis of facial features of terracotta warriors based on high-precision 3D point clouds

Yungang Hu[1,2*], Desheng Lan[3], Jingyang Wang[4], Miaole Hou[1,2], Songnian Li[5], Xiuzhen Li[3] and Lei Zhu[1,2]

Abstract

The striking realism of the life-sized ceramic terracotta warriors has been attracting the interest of the public and archaeologists since they were discovered from the mausoleum complex of the first Chinese Emperor Qin Shihuang in the 1970s. It is still debated whether the life-size models were based on individual people or were just crafted from the standardized models. This research examined the facial features of the terracotta warriors in a quantitative and contactless way with the support of the High-precision 3D point cloud modelling technology and the anthropometric method. The similarities and dissimilarities were analyzed among the facial features of terracotta warriors and 29 modern Chinese ethnic groups using mathematical statistics methods such as MDS, ANOVA, ranking analysis and cluster analysis. The results reveal that the features of the terracotta warriors highly resemble those of contemporary Chinese people and indicate that terracotta warriors were crafted from real portraits and intended to constitute a real army to protect the Emperor Qin Shihuang in the afterlife.

Keywords: Terracotta warriors, 3D point clouds, Facial features, ANOVA, MDS

Introduction

The discovery in 1974 of the terracotta army of the first emperor of China is known as one of the greatest finds in the history of twentieth-century archaeology. The army of terracotta warriors was created in the third century BC and comprises an estimated 7000 life-size soldiers standing in three pits that cover more than 20,000 square meters [1–3] and are located approximately 1.5 km from Qin Shihuang's mausoleum, as illustrated in Fig. 1. After discovery, the site became a museum and a UNESCO World Heritage Site in 1987; it remains one of the world's most impressive archaeological sites.

The terracotta warriors expertly crafted with intricate features and clothing demonstrate an extraordinarily high level of achievement from the artistic perspective and also provide an invaluable reference for studying the military, political, economic, cultural, scientific, and technological aspects of the Qin Dynasty [4, 5]. Therefore, the terracotta army attracts the public and scholars with diverse interests in ancient Chinese art, afterlife beliefs, funerary culture, craft technology, materials, logistics management and labor organization of building a mausoleum with such an incredibly large scale during ancient times.

One of the most extraordinary features is the striking realism of the terracotta warriors [6–8]. Each warrior has intricate details with distinct styled hair and features [9, 10]. They also have different builds, expressions and postures. Actually, the warriors were painted in proper colors when they were unearthed and originally equipped with real fully functional bronze weapons. Therefore, they should have appeared more realistic and individualized than now. But the colors have vanished after the warriors were exposed to the dry air. In addition, the armored soldiers present impressive funerary assemblage that

*Correspondence: huyungang@bucea.edu.cn
[1] School of Geomatics and Urban Spatial Informatics, Beijing University of Civil Engineering and Architecture, Beijing 100044, China
Full list of author information is available at the end of the article

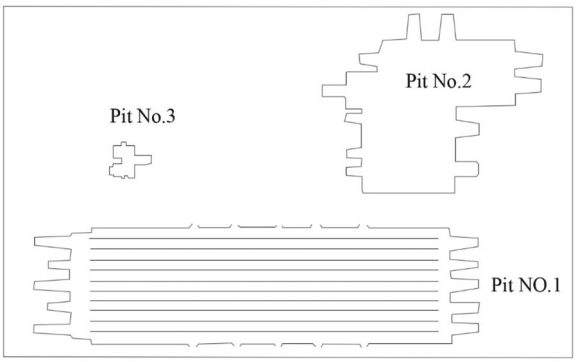

Fig. 1 Spatial distribution of the terracotta army's 3 burial pits

Fig. 2 Terracotta warriors in exploration T19 of Pit No. 1 (from Emperor Qinshihuang's Mausoleum Site Museum)

includes chariots, cavalry, horses, and archers installed in battle formations to protect the first emperor of China in the afterlife [11]. Figure 2 shows the warriors unearthed in exploration T19 of Pit No. 1.

Despite that there are intensive studies from different sectors since the discovery of terracotta warriors, it remains open how they were crafted and invented into these incredible works of art [10, 11]. Especially, it is still debated whether the life-size models were based on real humans or were just made from several standardized groups of models. It has led scholars to conduct related research into the realism of the terracotta army, delving into their purpose, materials used, the creative process, variability of figures, and similarity to the real humans.

Many researchers examined these sculptures of warriors in a qualitative way from the viewpoint of artistic sculpturing, purpose/function, cultural tradition, religious belief of an afterlife, and funeral ritual [6–9]. These related studies indicate that the terracotta warriors were intended to constitute a "real" underworld army to serve the first emperor in the netherworld after his death, as if he was alive. The constructed artificial army was more likely the substitution of his real army. Theoretically, this view conforms to the religious belief and funeral culture at that time [6, 7].

On the other hand, some researchers analyzed the unearthed warriors in a quantitative way, compared them with real humans. So far, the analysis of the body dimensions of terracotta warriors has indicated there is a remarkable resemblance to the modern population [13]. More detailed, the variability of the ear shape of the warriors was also examined and reveals that no two ears are strictly the same [12].

However, the facial features of terracotta warriors have not been analyzed quantitatively so far. It is still unclear how the features of these figures are exactly similar and different from the modern population. As well known, the face is essentially the most distinct feature used to identify individuals [14] and used as one of the main inputs in measuring anthropological variances among ethnic groups [15]. Compared to body features like body height, head and facial features are less affected by environmental factors and more significantly affected by genetic factors [16, 17]. This, in turn, means head and facial features could be used as one of the main factors to identify one person or ethnic group and even used to analyze the relationship between different ethnic groups.

Based on these research results and facts, theoretically, if the terracotta warriors were supposed to be crafted based on real people, each face of them should have distinct features as real humans have. Therefore, the quantitative analysis of the warriors would have a great significance in understanding whether the warriors were crafted based on the real portraits of Qin people. The analysis of similarity/dissimilarity of the warriors with contemporary Chinese people could provide useful clues for further research on the relationship between the ancient Qin people and the contemporary Chinese ethnic people.

This paper focused on the quantitative analysis of the facial features of warriors and comparison with contemporary Chinese people. The structure of this paper is as follows. "Data collection and measurements" section is focused on data collection, including the collection of the terracotta warriors' heads as well as 3D model construction, the measurements of key head and face features, and the collection of the head and face feature data of contemporary Chinese people. "Methodology of data analysis" section describes the main analysis methods used in this study. "Results and statistical analyses"

section introduces the analysis results of sample data, including multidimensional scaling analysis (MDS) for examination of the variability of facial features, and analysis of variance (ANOVA) for detecting the resemblance to the modern Chinese population. Conclusion and discussion are included in "Conclusion and discussion" section. The overall workflow of the study process is illustrated in Fig. 3.

Data collection and measurements

To build a precise 3D model of each sample, 3D laser scanning technology is used to capture 3D point clouds in this study. 3D laser scanning technology and computer vision or photogrammetry technology are able to acquire high-precision 3D data in archaeological research and applications [12, 18]. The technology provides new and unlimited access to fragile and valuable remains once 3D models are generated [19]. For instance, it contributes to the restoration of terracotta warriors in contactless virtual reality to reduce repeated contacts [20] or to the virtual color reconstruction of the Terracotta Army [21]. It also provides facial reconstructions as it was used for Robert the Bruce [22], or used to reveal otherwise hidden trauma such as in the examination of the Jericho skull [19].

3D data acquisition equipment

Considering the rich details of terracotta warriors and the need for data extraction accuracy, Faro arm platinum (Model 14000) was selected to scan the samples of terracotta warriors in this study, as its ideal scanning single point precision could reach up to 0.029 mm [23], which allows highly detailed feature capture of terracotta warriors. In this manner, each head model consists of 35 million 3D points on average, and the spatial resolution is high enough to support the needs of measurement in this study. The detectable minimum distance among points in the raw data on the nose area of a warrior is 0.032 mm, as shown in Fig. 4.

Following the 3D scanning process, post-processing software is needed to generate 3D models from point clouds. In this study, Geomagic 3D software (Geomagic Design X and Geomagic Wrap 2020) is adopted to build digital 3D models. In the meantime, it also provides efficient tools for measuring the head and facial features.

Statistical analysis software SPSS (official IBM SPSS Statistics) version 27 is selected for the qualitative data analysis. It is one of the most powerful tools for complex statistical data analysis in various kinds of research fields. In this study, SPSS is mainly used to implement the MDS, ANOVA, Cluster analysis.

Sample selection

As mentioned in "Introduction" section, the terracotta army is distributed into three pits and is comprised of an estimated 7000 warriors, approximately 6000 of which are located in Pit 1. Thus far, approximately about 1500 pieces have been unearthed [24]. The samples used in our

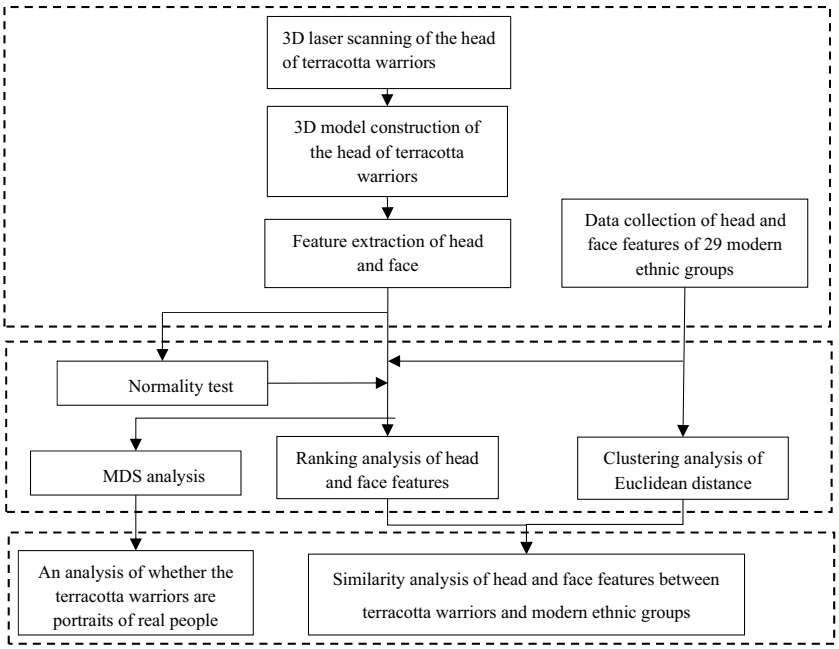

Fig. 3 Overall process of the study

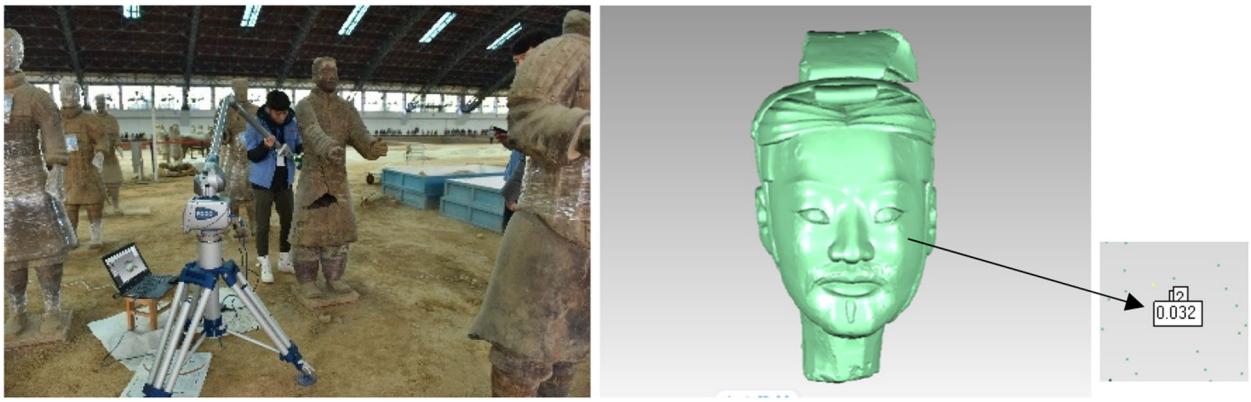

Fig. 4 The laser scanner used in this study and its resolution

study are from a random selection of warriors located in the largest and most famous Pit No. 1.

The excavation of Pit 1 was divided into 27 explorations, among which 6 areas were excavated and cleaned. The specific locations of the 6 excavated and cleaned areas are shown in Fig. 5, with numbers T1, T2, T10, T19, T20 and T23 [1].

Our 58 research samples were randomly selected from T19, T20, and T23, and the numbers of terracotta warriors arranged in the three areas were 218, 220 and 200. 20, 11 and 27 terracotta warriors were randomly selected respectively from the three areas respectively. The overall arrangement and sample locations are shown in Fig. 6.

Definition of terracotta warriors' key facial features

To obtain quantitatively the variation of facial features of terracotta warriors, the anthropometric method is adopted to measure the physical dimensions of each warrior in this study. Due to the quantitatively and objectively descriptive ability and objectivity anthropometric method, many researchers used it for the analysis of humanoid sculpture relics based in archaeology [25–28].

The head and facial features in anthropometry are based on five measurement dimensions, including height, length, breadth, angle, circumference and radian, all further subdivided into 54 features. These characteristics and indices are clearly defined in the Anthropometric Manual [29] and are specifically described in Chinese national and international standards related to anthropometry [30]. Because of the decorative parts of warriors' heads such as the bun and the crown as shown in Fig. 7, some head features are unavailable such as the head circumference, maximum head breadth and maximum head length.

Each defined feature and index can describe a characteristic or variation among faces. However, they vary due to descriptive ability and possible errors by operators. According to the study [31, 32], 14 selected facial landmarks used for measuring facial features can be used to create a dense corresponding mesh to capture

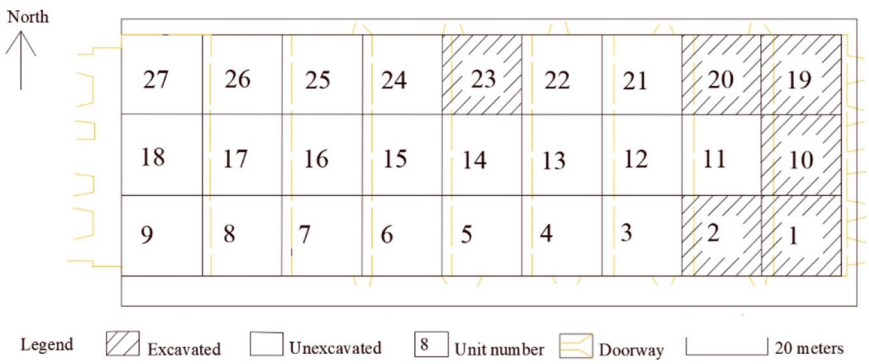

Fig. 5 Schematic diagram of the exploration of Pit 1

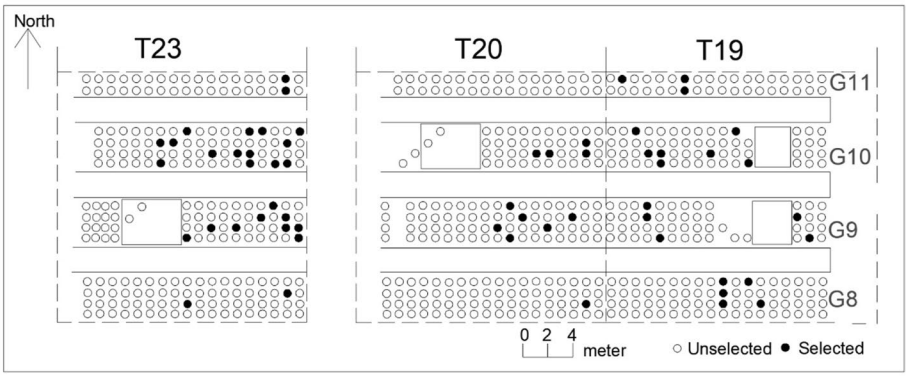

Fig. 6 The spatial distribution of terracotta warrior samples in this study

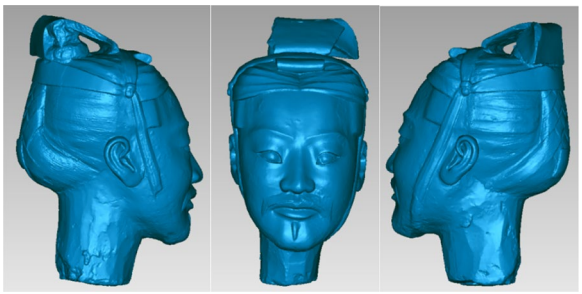

Fig. 7. 3D mesh models of the terracotta warriors' heads

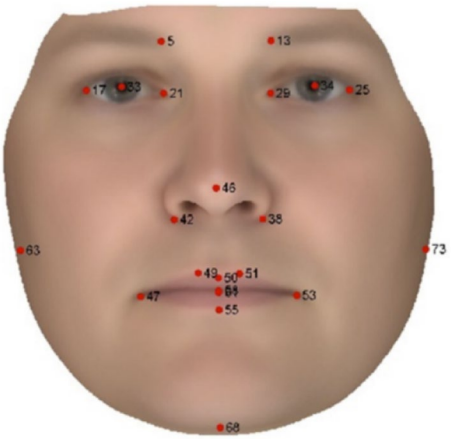

Fig. 8 Key landmark points selected by the study of Fagertun et al. [32]

as many facial features as possible, as shown in Fig. 8. Thus, we can use fewer features to capture the main facial variance and reduce the noise in recognizing and measuring facial shapes.

Another important factor in the key feature selection considered in this study is the limitation of accessible historical data on facial features of modern populations used for comparison with terracotta warriors.

Considering these two main factors, it is unnecessary or impossible to use all features described above in this study. As a result, 8 key features and 2 indices were selected and used for measuring and comparing the facial features of warriors and modern populations, as illustrated in Fig. 9. Comparing Figs. 8 and 9, we can see that the 8 key features basically cover the landmark points selected in the study [31, 32].

The definitions of the 8 key features in Fig. 9 above are described as follows [33–35].

1. Biocular breadth: Distance between the ectocanthions of the left and right eyes. Ectocanthions refer to the point where the upper and lower eyelid edges meet on the outer corner of the eye fissure.
2. Interocular breadth: Distance between the entocanthions of the left and right eyes. Entocanthions refer to the point where the upper and lower eyelid edges meet on the inner corner of the eye fissure.
3. Morphological facial length: The distance from sellion to gnathion. Sellion is the most concave point of the nose bridge. Gnathion refers to the lowest point of the chin on the midsagittal plane when the head is positioned with the OAE (Frankfurt horizontal plane).
4. Bizygomatic breadth: The distance between the left and right zygions. Zygion refers to the most prominent point on the zygomatic arch on the outside of the face.
5. Nose breadth: Distance between the left and right alares. Alare refers to the outermost point of nose alar.
6. Nose height: The distance from sellion to subnasale. The subnasale is the turning point of the nasal septum to the upper lip.

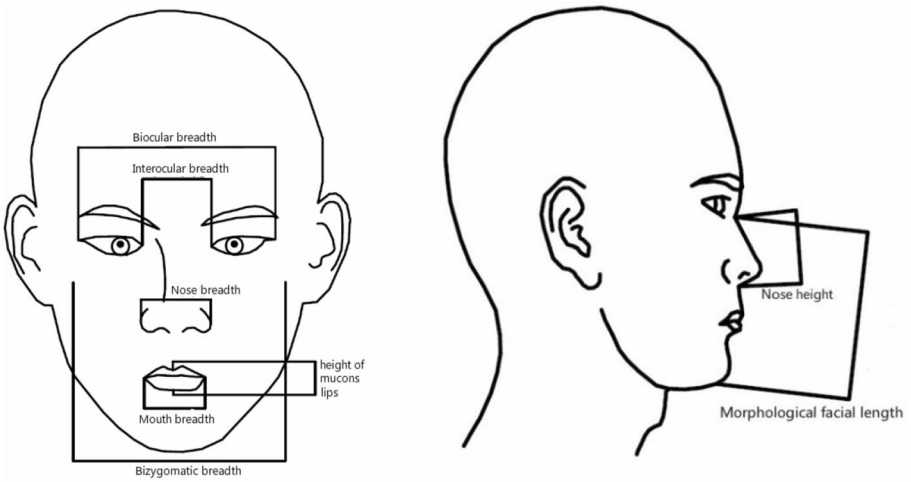

Fig. 9 Schematic diagram of measurement features

7. Height of mucon lips: The distance from the labrale superius to the labrale inferius. Labrale superius refers to the intersection of the upper lip edge and the midsagittal plane. Labrale inferior refers to the lower lip edge intersection and midsagittal plane.
8. Mouth breadth: The distance between the left and right cheilions when the mouth is naturally relaxed. Cheilion refers to the point where the upper and lower lip edges meet at the outer end.

In addition, the morphological facial index and nasal index can be calculated, which are mainly used to judge the width of the face and nose of terracotta warriors.

1. Morphological facial index = (morphological facial length/bizygomatic breadth) * 100, reflecting the width and narrowness of the face; the larger the value, the narrower the face.
2. Nasal index = (nose breadth/nose height) * 100, reflecting the width of the nose. The larger the value is, the wider the nose.

Measurement of terracotta warriors' heads and facial features

The traditional measurement of head and facial features is to directly measure the head and face of a real person using various tools, such as bending foot gauges and straight foot gauges [36]. The accuracy of measurement is approximately 0.1 mm. However, there exists the risk of damage to cultural relics in the traditional manual measurement method. The measurement of head and facial features on the high-precision 3D model of terracotta warriors could be automatically extracted by an algorithm or manually measured by computer aiding software. These feature points include corner points (ectocanthions, cheilions), inflection points (sellions, gnathions, zygions, alares, subnasales) and lip midpoint (labrale superius, labrale inferius).

Taking the head of a terracotta warrior, number G9-10 as an example, we described the process of measuring the 8 head and facial features. Figure 10 illustrates a schematic diagram of measuring each feature: (a) biocular breadth, (b) interocular breadth, (c) morphological facial length, (d) bizygomatic breadth, (E) nose breadth, (f) nose height, (g) height of mucons lips, (h) mouth breadth.

Head and face data collection from contemporary Chinese population

To compare the heads and faces of warriors and those of contemporary population, the head and face data of 29 ethnic groups were collected from of the past studies. The associated geographical distribution is illustrated in Fig. 11. The mean values of the 8 key facial features are listed in Table 1. These ethnic groups cover most regions of China, accounting for 2/3 of ethnically Chinese population which can be used to comprehensively analyze the distant and near relationship between terracotta warriors and the modern Chinese population.

Methodology of data analysis

In this paper, a quantitative and more precise analysis is conducted to assess the facial variability of the terracotta warriors with 3D laser scanning technology and statistical methods. Furthermore, in order to examine the similarities and dissimilarities of the key head and facial features between terracotta warriors and contemporary

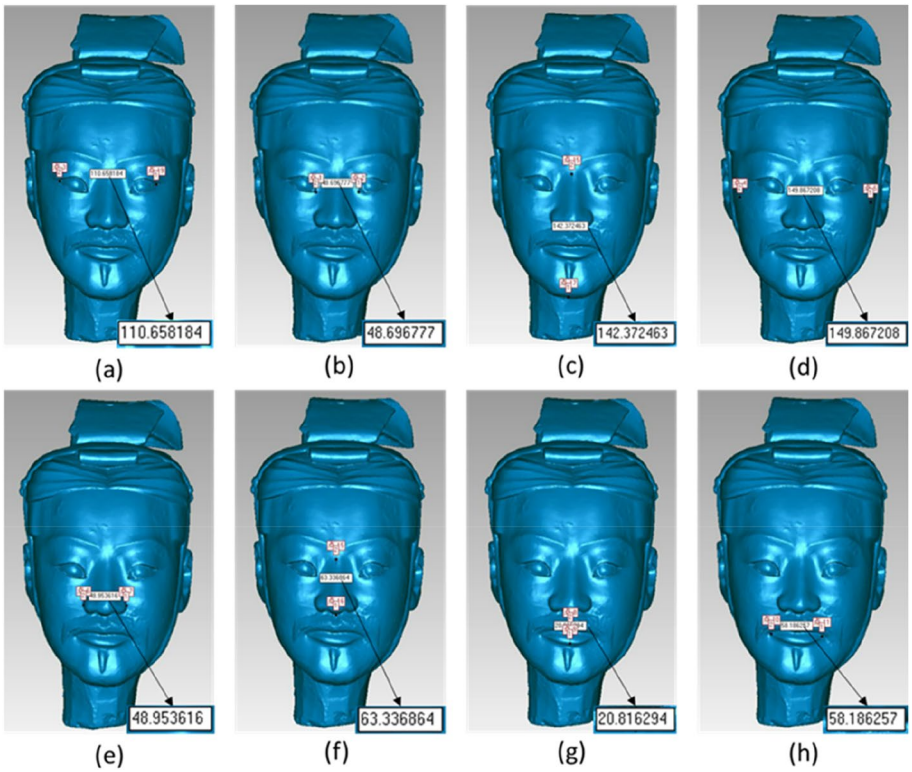

Fig. 10 Schematic diagram of feature measurements in millimetres. **a** Biocular breadth, **b** interocular breadth, **c** morphological facial length, **d** bizygomatic breadth, **e** nose breadth, **f** nose height, **g** height of mucon lips, **h** mouth breadth

Chinese populations, AVOVA and Cluster analysis method are employed.

Normality test of samples

Statistically, the normality test is to check if the distribution of samples used in this study conforms to a normal distribution. There exist more than 40 test methods available in the statistical literature. The Kolmogorov–Smirnov test (K–S test) is used in this study due to the fact that it has more general use in different areas and data analysis than other tests.

The Kolmogorov–Smirnov (K–S) test is a nonparametric hypothesis and distribution-free test in which there is no assumption about the distribution of data [64]. Therefore, it is a more universal test method without restriction on the size of the sample and is widely supported by statistical software such as SPSS (Statistical Package for the Social Sciences) and SAS (Statistical Analysis Software) [65]. However, it is noted that there is a restriction when the original K–S test is applied to the normality test in which the parameters of the hypothesized distribution are supposed to be known completely. Therefore, in this study, a modification of the K–S test, the Lilliefors test, is adopted, in which the parameters are allowed to be estimated based on the sample [66]. This test is performed based on the formula below.

$$D = Max_x|F*(X) - S_n(X)|, \tag{1}$$

where $S_n(X)$ is the sample cumulative distribution function and F^* (X) is the cumulative normal distribution function with $\mu = X$, the sample mean and $s2$, the sample variance, defined with denominator $n-1$.

Clustering analysis

The method of cluster analysis is often used in the classification of races in anthropology [67–69]. The purpose of cluster analysis is to divide objects into several clusters based on their similarity so that objects in the same cluster are highly correlated, while objects in different clusters are low correlated [70]. The specific step includes calculating the distance between characteristic values between two clusters, merging the two clusters with the smallest distance into a new cluster, and taking

Fig. 11 Geolocation distribution of selected samples from the modern Chinese population

the average value as the feature value of the new cluster. Then, the process is repeated until all clusters are merged into one and the clustering ends [71].

Euclidean distance is commonly used in clustering calculations to measure the distance of individuals in space. The larger the distance is, the greater the gap; otherwise, it will be closer. The calculation formula is as follows (2):

$$D_{ij} = \sqrt{\sum_{i=1}^{n} (x_i - y_i)^2}. \tag{2}$$

Finally, to verify the statistical significance of cluster analysis, ANOVA was conducted on the head and facial features of terracotta warriors and 29 modern ethnic groups to infer the probability of difference or to compare whether the difference between the two variables was significant. If the p value in the test result is less than 0.05, it means that there is a significant difference between the two groups. In contrast, the larger the p value is, the smaller the difference [72].

MDS analysis

Multidimensional scaling (MDS) is a visual representation of dissimilarities (or similarities) among objects. MDS is a multivariate data analysis technique that can represent higher-dimensional data in lower space and transform dissimilarity measurements into distances on a spatial map [73]. On the spatial map, the dissimilar objects are further apart, while similar objects are placed closer to each other. As such, MDS provides us with a spatial and intuitive data analysis method. Most MDS algorithms use Euclidean principles, where the distance (d_{ij}) between points i and j is defined as follows:

$$d_{ij} = \sqrt{\sum_{a} (x_{ia} - x_{ja})}, \tag{3}$$

where x_i and x_j represent the coordinates of points i and j on dimension a, respectively.

MDS analysis can be found in most statistical software, such as SPSS or SAS. It has been widely applied

Table 1 Key facial features of 29 Chinese ethnic group (unit: mm)

Number	Ethnic groups	Morphological facial length	Bizygomatic breadth	Nose height	Nose breadth	Height of mucons lips	Mouth breadth	Binocular breadth	Interocular breadth	Data source (reference)
N1	Northern Han	126.80	142.80	53.90	38.70	16.30	51.60	91.80	36.60	Yu et al. [37]
N2	Southern Han	124.10	144.80	54.40	38.90	16.60	51.20	89.80	34.10	Yu et al. [37]
N3	Hui	121.27	141.65	50.66	37.30	17.26	49.41	86.40	33.84	Zheng et al. [38]
N4	Mongolian	122.62	147.61	52.25	35.09	17.45	50.49	102.04	33.96	Zhu et al. [39]
N5	Uighur	126.00	145.00	56.30	35.00	16.10	49.60	97.50	34.10	Ai et al. [40]
N6	BuYi	115.00	140.80	50.80	38.20	15.80	50.50	85.00	33.90	Zheng et al. [41]
N7	Wa	127.40	142.30	56.30	38.80	19.70	52.80	91.20	33.10	Zheng et al. [42]
N8	Uzbek	121.70	145.70	52.70	34.90	13.30	51.40	94.20	31.20	Zheng et al. [43]
N9	Khmus	123.40	141.20	57.60	38.70	19.60	51.50	93.70	35.70	Zheng et al. [44]
N10	Dong Xiang	128.66	140.14	56.36	35.95	16.17	52.80	87.68	34.44	Dai and Yang [45]
N11	Tibetan	115.10	138.36	52.93	32.11	15.84	52.76	101.95	35.55	Hai and Dai [46]
N12	Kazakh	125.60	150.40	56.20	35.50	16.60	50.30	100.10	35.00	Cui et al. [47]
N13	Daur	121.30	143.70	50.40	36.20	17.30	50.60	104.10	34.80	Shi et al. [48]
N14	Yi	128.30	142.80	51.30	38.10	17.10	56.00	89.60	30.70	Pang et al. [49]
N15	Kirgiz	126.99	149.37	56.88	38.38	18.97	52.54	91.65	31.70	Shao et al. [50]
N16	Jingpo	123.74	139.53	51.87	38.94	18.22	53.32	102.72	35.84	Li et al. [51]
N17	Hezhe	121.60	143.10	52.70	38.10	17.10	48.80	90.30	36.90	Shi et al. [52]
N18	Man	125.34	144.85	53.13	37.36	18.77	50.94	94.46	35.88	Han et al. [36]
N19	Xibo	133.27	147.68	58.40	38.48	18.07	52.90	103.10	35.47	Shao et al. [53]
N20	Tajik	124.42	139.08	55.07	32.24	15.26	52.87	100.11	34.24	Shao et al. [54]
N21	Naxi	124.97	141.18	56.90	38.57	15.59	53.35	100.18	35.15	Liu et al. [55]
N22	Yugur	135.03	130.67	62.94	37.40	15.60	50.10	90.75	35.40	Dai et al. [56]
N23	Dong	113.68	131.62	49.08	38.85	19.04	50.38	96.03	33.22	Pi et al. [57]
N24	Miao	116.38	127.62	51.08	37.34	15.04	50.58	96.53	31.82	Pi et al. [58]
N25	Li	121.02	140.39	54.98	40.35	22.36	47.66	94.07	38.05	Zhang and Zhang [59]
N26	Bao'an	128.63	140.33	56.06	35.41	15.15	50.14	86.39	33.33	Yang and Dai [60]
N27	Dai	126.60	141.80	51.70	38.80	16.60	50.20	89.80	31.50	Zhang et al. [61]
N28	Korean	125.47	142.98	55.62	37.51	18.81	50.98	98.51	33.71	Jin and Jin [62]
N29	Zhuang	121.10	142.70	53.80	40.40	21.14	49.50	92.00	36.40	Zhang and Zhang [63]

Table 2 Measurements of head features of terracotta warriors (unit: mm)

Number	Biocular breadth	Interocular breadth	Morphological facial length	Bizygomatic breadth	Nose breadth	Nose height	Height of mucons lips	Mouth breadth
1–57	102.26	43.43	127.17	127.19	41.10	51.09	15.62	55.75
5–14	96.70	39.99	120.74	135.57	43.44	56.51	18.65	52.79
23	106.82	42.61	120.26	142.24	46.68	47.30	22.50	48.23
35	109.41	50.30	126.26	149.21	37.19	56.66	18.28	53.08
49–65	104.95	37.17	131.60	150.21	51.99	52.12	20.11	62.05
55, 78, 96	109.05	49.75	131.40	139.14	51.39	58.71	21.68	63.57
G8 58–59	118.18	51.97	131.02	135.40	50.32	58.79	22.10	64.28
G8 90–95	103.33	38.86	125.96	141.66	50.71	49.61	16.28	55.87
G8-23	103.36	41.94	118.91	146.38	46.79	48.16	23.21	44.89
G8-25, 70, 96	110.02	50.74	124.56	144.09	51.24	52.40	22.30	58.72
G8-34	107.77	37.91	134.49	151.10	56.16	53.19	22.34	58.67
G8-40	108.92	48.00	122.61	135.08	39.22	54.32	17.49	52.98
G8-46–91	105.53	42.48	130.22	129.28	49.45	54.65	20.14	55.06
G8-70	102.42	36.52	124.36	125.80	44.42	57.43	18.07	50.31
G8-77	104.86	41.83	127.07	143.17	48.50	53.97	18.09	56.26
G9-3	116.25	50.78	141.03	142.14	47.12	63.98	21.01	61.66
G9-4	99.89	42.14	130.15	132.99	47.51	58.99	21.71	58.93
G9-6	112.13	49.81	141.09	141.54	48.95	65.17	22.30	59.70
G9-7	99.31	45.47	126.15	123.43	46.32	56.16	19.94	51.15
G9-8	101.02	47.83	122.17	140.84	46.22	53.79	22.81	55.75
G9-9	96.23	39.16	115.81	120.44	45.49	54.40	19.35	44.64
G9-10	110.66	48.70	141.08	149.87	48.95	65.82	20.81	63.68
G9-14	100.81	48.27	128.20	126.74	45.11	58.16	21.05	49.10
G9-23	95.87	41.62	123.81	122.03	46.43	57.68	21.15	43.61
G9-31	93.95	35.60	122.37	126.37	45.56	51.43	18.57	51.90
G9-45	106.50	43.95	137.98	136.10	47.54	56.44	22.13	58.23
G9-63	110.59	46.74	137.94	135.35	51.04	55.66	23.42	56.33
G10-8	115.28	50.43	138.04	140.62	50.73	61.04	23.15	60.81
G10-12	95.05	37.08	129.86	128.45	47.73	58.89	16.66	55.54
G10-13	119.34	53.21	141.30	137.48	50.01	62.27	22.90	65.47
G10-15	105.53	49.97	123.75	139.00	52.31	51.18	18.50	59.70
G10-16	120.89	53.98	141.54	149.95	52.84	59.94	23.03	66.23
G10-17	105.45	47.17	132.00	132.86	53.88	53.35	21.14	63.80
G10-19	96.64	40.50	129.44	122.00	45.04	59.97	19.16	58.72
G10-20	99.55	41.32	130.09	124.70	45.88	60.18	19.50	60.42
G10-23	114.72	49.92	141.04	136.74	49.92	65.87	22.65	60.77
G10-26	97.44	41.88	129.36	142.35	45.96	58.89	22.58	61.63
G10-37	97.31	42.01	130.10	121.15	43.69	60.99	19.41	58.98
G10-42	117.57	50.76	140.32	131.87	51.51	61.08	21.59	60.46
G10-47	112.01	48.39	141.20	140.50	49.99	60.04	19.03	58.15
G10-50	100.99	42.48	129.13	128.97	46.14	59.45	18.36	59.57
G10-52	108.68	43.52	131.77	136.51	47.90	56.45	20.16	54.66
G10-53	113.77	51.95	141.05	132.06	48.96	64.13	20.82	59.24
G10-67	107.94	43.94	138.23	133.35	51.11	65.33	19.65	63.10
G10-72	98.25	36.28	122.62	134.89	45.53	54.08	22.31	54.21
G10-79	99.64	42.03	132.13	139.77	44.64	59.42	20.92	56.50
G10-83	115.86	49.32	141.08	130.36	47.32	64.88	22.95	61.54
G10-86	99.43	46.62	123.17	123.97	44.67	53.87	20.54	50.71

Table 2 (continued)

Number	Biocular breadth	Interocular breadth	Morphological facial length	Bizygomatic breadth	Nose breadth	Nose height	Height of mucons lips	Mouth breadth
G10-88	115.99	51.20	139.62	143.39	51.02	63.15	21.46	57.28
G11-24	96.08	36.12	127.85	135.35	43.69	59.02	21.82	57.79
G11-23	102.82	41.39	136.78	132.50	52.15	61.51	20.10	61.27
G11-33	103.30	45.96	130.04	142.58	48.98	51.77	21.20	51.44
G11-50	106.39	44.25	130.64	133.14	49.05	50.79	22.99	53.54
G11-51	103.84	41.79	137.00	148.05	47.70	57.36	17.75	52.80
G18-01	108.48	48.34	127.36	140.53	46.96	53.89	20.18	51.71
WBH-01	113.89	51.23	139.58	132.38	49.89	61.71	20.16	61.58
YT-01	99.23	40.96	132.01	124.24	45.22	61.72	20.82	55.89
YT-06	109.61	46.09	130.92	124.16	44.54	58.81	18.33	66.05
Mean value	105.82	44.89	131.09	135.47	47.75	57.48	20.53	57.01
Standard deviation	7.01	4.99	6.93	8.32	3.49	4.65	1.93	5.33

Table 3 Normality test results with the Kolmogorov–Smirnov (K–S) test method

Name	Size	Mean	Standard deviation	Skew	Peak	Kolmogorov–Smirnov (D) value	p
Biocular breadth	58	105.823	7.014	0.276	− 0.849	0.081	0.453
Interocular breadth	58	44.891	4.993	− 0.1	− 1.065	0.107	0.095
Morphological facial length	58	131.094	6.928	0.007	− 0.943	0.114	0.057
Bizygomatic breadth	58	135.469	8.32	0.011	− 0.835	0.072	0.638
Nose breadth	58	47.755	3.49	− 0.414	0.866	0.066	0.762
Nose height	58	57.476	4.648	− 0.087	− 0.661	0.087	0.33
Height of mucons lips	58	20.533	1.93	− 0.516	− 0.447	0.091	0.264
Mouth breadth	58	57.013	5.325	− 0.521	− 0.048	0.088	0.325

*P < 0.05

Table 4 Head index classification of terracotta warriors

Indexes	Classification	Number	Percentage (%)
Classification of morphological facial index	Hyperouryprosopy (X-78.9)	0	0.00
	Curyprosopy (79.0–83.9)	1	1.72
	Mesoprosopy (84.0–87.9)	5	8.62
	Loptoprosopy (88.0–92.9)	11	18.97
	Hyperleptoprosopy (93.0-X)	41	70.69
Classification of nasal index	Ultraleptorrhiny (X-39.9)	0	0.00
	Hyperleptorrhiny (40.0–54.9)	0	0.00
	Leptorrhiny (55.0–69.9)	1	1.72
	Mesorrhiny (70.0–84.9)	38	65.52
	Platyrrhiny (85.0–99.9)	15	25.86
	Hyperplatyrrhiny (100.0–114.9)	4	6.90
	Ultraplatyrrhiny (115.0-X)	0	0.00

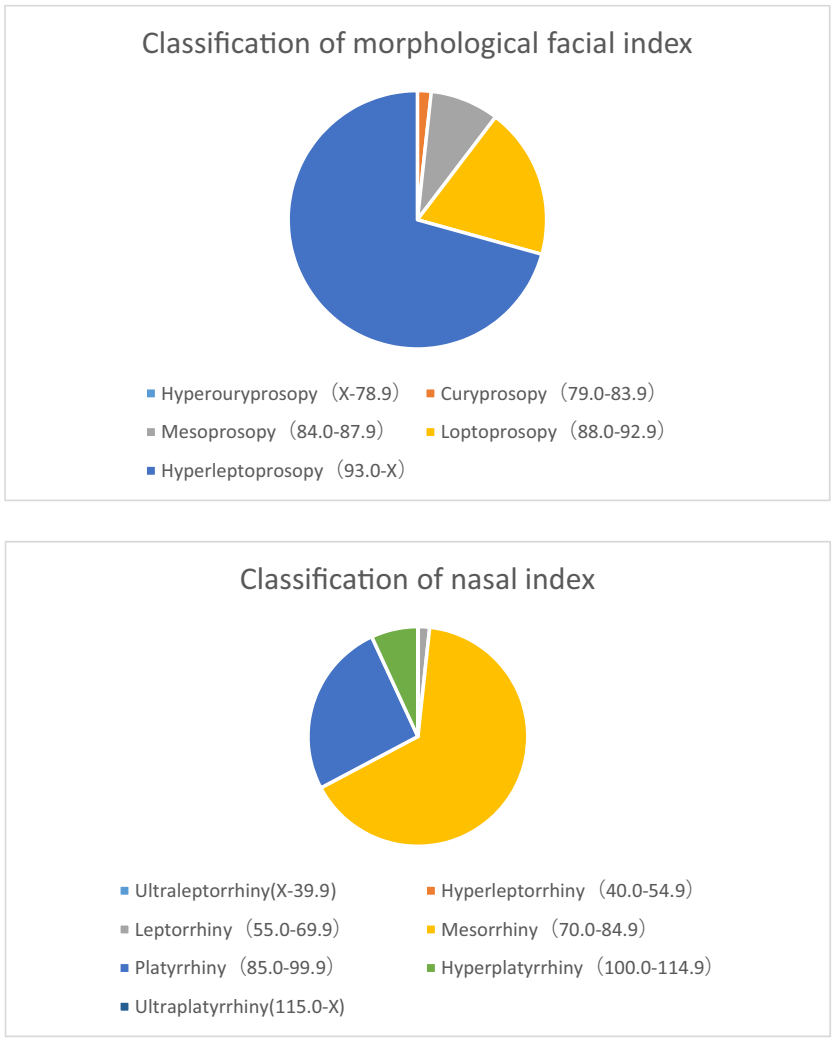

Fig. 12 The distribution of facial and nasal indices

in many fields, such as biology, artificial intelligence, neural networks, image analysis, and ecology, even in psychological research [74]. In the field of archaeology and culture relics, MDS has provided intuitive, effective and valuable ways to analyze dissimilarities or similarities [75]. In this paper, MDS is applied in the analysis and spatialized representation of dissimilarities among facial features of the terracotta warriors.

ANOVA

Analysis of variance (ANOVA) is a statistical technique that is used to determine if two or more groups are significantly different from each other. ANOVA checks the impact of one or more factors by comparing the means of different samples. It can reduce the compounded effect on the error rate of the result pairwise test like T-test method. ANOVA was developed by the English statistician Yates and Fisher [76] and has been applied in various fields for data analysis. It has been applied successfully to face recognition and classification [77, 78]. In this paper, ANOVA is utilized to compare the differences among facial features of terracotta warriors and modern Chinese ethnic groups.

Results and statistical analyses

Measurement results

According to the measurement method described in "Definition of terracotta warriors' key facial features" section, the head and facial features of 58 terracotta warriors were measured. All measurement results are shown in

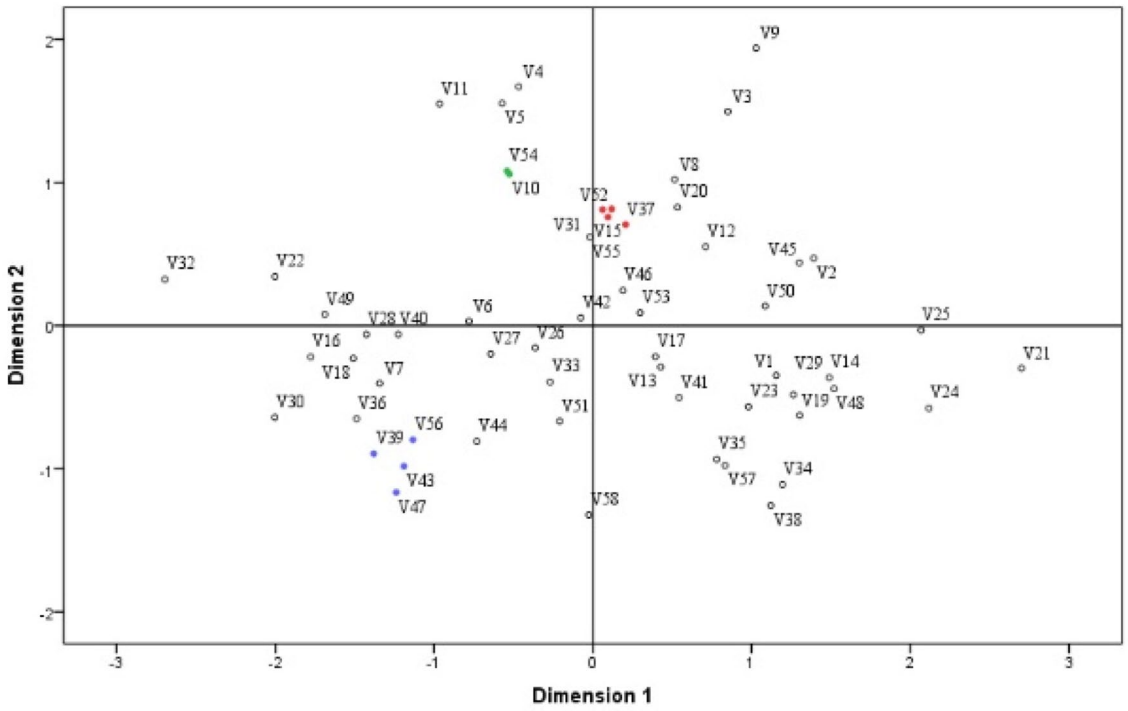

Fig. 13 Result of MDS analysis

Table 2. The mean values listed in the table are the 8 head and facial feature values of the sample data obtained.

As described in "Normality test of samples" section, Kolmogorov–Smirnov (K–S) (actually its modification, Lilliefors test) is applied to implement the normality test. The test results illustrated in Table 3 indicate that 8 independent variables of facial features conform to a normal distribution.

The morphological facial and nasal indices of the sample data were also calculated, the sample number at different index intervals was counted (Table 4), and the quantity distribution charts were generated (Fig. 12). From the above data, it is interesting to note that most of the 58 samples are within the hyperleptoprosopy and mesorrhiny types. According to investigation results from Yu et al. [37], there are more males of northern Chinese Han individuals that belong to hyperleptoprosopy and mesorrhiny types than males of the southern Chinese Han ethnicity. This shows that the face form and nasal shape of terracotta warriors are closer to those of the northern Han population.

In order to assess the precision of measurement via 3D model in this study, a comparison was made with the traditional contact measurement method using a millimeter. Table 5 illustrates the measurement precision of interocular breadth based on the actual face of a terracotta warrior and based on its 3D model. The result shows that the precision of the 3D model measurement is 0.30 mm, while the precision of the traditional method is 0.79 mm. The contactless method can obtain more accurate measurement results than the traditional contact method. The main reason lies in the fact that he high-resolution/density 3D model could ensure that an operator positions at the same location at each time of measurement as possible as he can.

Variability of terracotta warriors' heads and faces

The MDS method was applied in analyzing the variability of 58 terracotta warrior samples randomly selected. The overall result is shown in Fig. 13. The label beside each dot represents the number of each terracotta warrior. The further the distance between the two dots is, the more different they are.

It can be observed from Fig. 13 that the distribution of dots is scattered and random, and no two dots are identical. This chart reveals that the fact the faces of warriors appear great variability of key facial features. Each terracotta warrior has distinct facial features, which seem like real humans. That means the MDS analysis result supports the theory that the warriors were based on a

Table 5 Comparison of precision between the traditional method and 3D model-based method

Order number	Traditional method (mm)	Via 3D model (mm)
1	45.30	43.84
2	43.70	44.33
3	43.44	44.11
4	44.12	44.51
5	43.80	44.39
6	44.68	44.73
7	45.70	44.84
8	43.14	44.94
9	45.18	44.46
10	45.04	44.48
11	45.12	44.56
12	45.18	44.51
13	45.08	44.52
14	43.44	44.82
15	44.98	44.95
16	43.24	44.86
17	44.12	44.88
18	43.64	44.40
19	44.50	44.20
20	44.72	44.33
Mean	44.41	44.53
Standard deviation	0.79	0.30

real army. Actually, this inference is also consistent with the funeral tradition and culture around Qin Dynasty. At that time, people viewed the afterlife as an extension of worldly life. Thereby, tomb builders always pursued to duplicate all aspects of the real world in the netherworld, including everything they needed [7]. Therefore, it is reasonable that Qin Shihuang, as the first China emperor who unified the vassal states, established the "real army" in his necropolis to protect himself in the afterlife. Besides thousands of warriors, almost five hundred weapons such as spears and swords, and more than ten thousand scattered arrowheads have been found in pit no. 1 [5]. Sima Qian, a Han Dynasty historian who lived about a century after the first emperor's time, also mentioned that the tomb of Qin Shihuang was intended to replicate the real world in his "Shiji" (Records of the Grand Historian). Therefore, theoretically, it is more reasonable that each life-sized terracotta soldier was modeled on an actual person.

However, some dots are noticed to be very close. For example, the group of red green or blue dots in Fig. 13 are closer than the others. This can be verified from the 3D head and face models of the warriors, as shown in Fig. 14, the faces in the same box look more alike. In Fig. 14, the face number under each face model, the first part such as "G11-51", "G8-25" represent the location of warriors in the Pit no. 1, the second part such "v10", "v54" represents the number used in Fig. 13. This situation is like the real world of human beings, on the contrary, it increases the realism of terracotta warriors.

Variation of heads and faces between terracotta warriors and modern ethnic groups

The differences between the terracotta warriors and modern ethnic groups by size of facial features were examined. First, the 8 head and facial features were sorted according to their values. According to the sorting results (Fig. 15), 6 of the 8 facial features were neither at the maximum nor at the minimum, which falls into the range of the facial features of the 29 ethnic groups. The 6 facial features include morphological facial length, bizygomatic breadth, nose height, the height of mucons lips, mouth breadth and biocular breadth. However, it should be noted that one of the very interesting points is that nose breadth and eye breadth (interocular) are beyond the range of facial feature values of contemporary Chinese ethnic groups. Table 6 lists the statistical mean and standard deviation of key facial features of terracotta warriors and 29 modern Chinese ethnic groups.

This indicates that 75% ($6/8=0.75$) of the terracotta warriors overlapped the range of the head and facial feature values of modern multiethnic groups. Therefore, there was little difference in the head and face features between the terracotta warriors and modern multiethnic groups. The key features of the terracotta warriors highly resemble those of modern Chinese populations. Terracotta warriors seem like one of Chinese ethnic groups.

Clustering analysis results based on Euclidean distance

According to the above Euclidean distance cluster analysis formula, the Euclidean distance between the terracotta warriors and other ethnic groups is shown in Table 7. Then, cluster analysis was performed based on distance values, and the cluster graph was generated by SPSS. The results are shown in Fig. 16.

From the results of cluster analysis, we can see that these ethnic groups are divided into three main groups (Fig. 16). The terracotta warriors belong to Group 2,

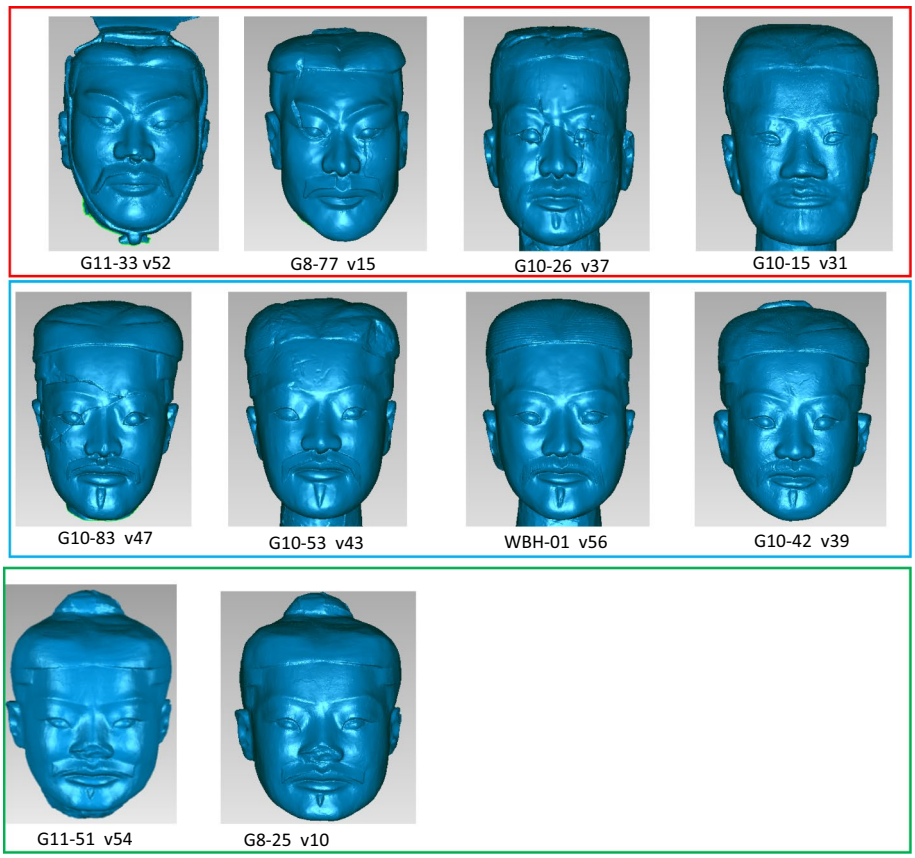

Fig. 14 Similarities and differences among the faces of terracotta warriors (the images in the red, blue and green rectangles correspond to the same color dots in Fig. 13)

which has ethnic groups such as N4-Mongolian, N16-Jingpo, N19-Xibo, N21-Naxi, N28-Korean, N13-Daur, N12-Kazakh, N22-Uygur, N20-Tajik, and N11-Tibetan. Among them, nine (N4-Mongolian, N16-Jingpo, N19-Xibo, N21-Naxi, N13-Daur, N12-Kazakh, N22-Uygur, N20-Tajik, and N11-Tibetan) belong to western ethnic groups, which indicates that the relationship between the terracotta warriors and these ethnic groups is closer. According to the comparison of the D_{ij} values, the terracotta warriors are close to N4-Mongolian ($D_{ij}=16.347$) in facial features, followed by N16-Jingpo ($D_{ij}=16.418$) and N19-Xibo ($D_{ij}=16.452$).

Further ANOVA implementation results (Table 8 and Fig. 17) also reveal that the faces of terracotta warriors resemble the modern Chinese population in six key facial parameters. In particular, the terracotta warrior's facial features resemble modern Chinese populations in morphological facial length, nose height, height of mucons lips much more than in other key features. Only in nose breadth and eye breadth (interocular) was there a statistically significant difference among all 29 ethnic groups, and the mean value exceeded all 29 ethnic groups. One of the possible reasons for this difference might be the procedure of producing terracotta warriors when they were made at high temperatures. Another possible reason is the face evolution of human beings caused by climate change and dietary changes [79, 80]. Further reasons need to be revealed with more archeological material and analysis.

Conclusion and discussion

The striking realism of terracotta warriors has led to hypothesize or believe that they were based on real soldiers who served in the emperor's army. But few researchers examined quantitatively in statistical methods the

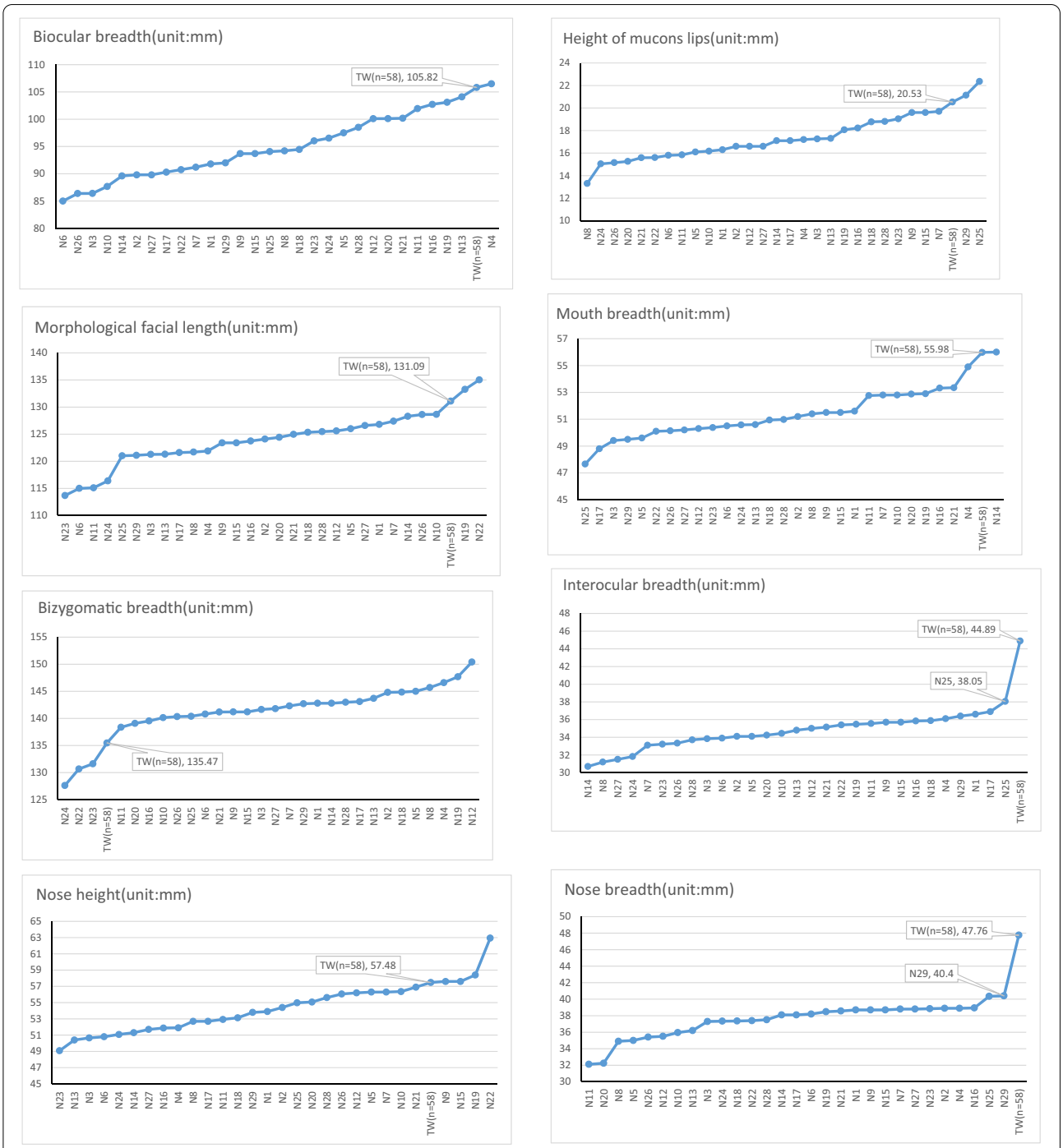

Fig. 15 Numerical sequence of eight head and facial features of terracotta warriors and different ethnic groups (unit: mm)

Table 6 The mean and standard deviation of terracotta warriors and 29 Chinese ethnic groups

Number	Name	Biocular breadth	Interocular breadth	Morphological facial length	Bizygomatic breadth	Nose breadth	Nose height	Height of mucons lips	Mouth breadth
	TW (n = 58)	105.82 ± 7.01	44.89 ± 4.99	131.09 ± 6.93	135.47 ± 8.32	47.76 ± 3.49	57.48 ± 4.65	20.53 ± 1.93	55.98 ± 4.33
N1	Northern Han	91.8	36.6	126.8	142.8	38.7	53.9	16.3	51.6
N2	Southern Han	89.8	34.1	124.1	144.8	38.9	54.4	16.6	51.2
N3	Hui	86.4	33.84	121.27	141.65	37.3	50.66	17.26	49.41
N4	Mongolian	106.5	36.1	121.9	146.6	38.9	51.9	17.2	54.9
N5	Uighur	97.5	34.1	126	145	35	56.3	16.1	49.6
N6	BuYi	85	33.9	115	140.8	38.2	50.8	15.8	50.5
N7	Wa	91.2	33.1	127.4	142.3	38.8	56.3	19.7	52.8
N8	Uzbek	94.2	31.2	121.7	145.7	34.9	52.7	13.3	51.4
N9	Khmus	93.7	35.7	123.4	141.2	38.7	57.6	19.6	51.5
N10	Dong Xiang	87.68	34.44	128.66	140.14	35.95	56.36	16.17	52.8
N11	Tibetan	101.95	35.55	115.1	138.36	32.11	52.93	15.84	52.76
N12	Kazakh	100.1	35	125.6	150.4	35.5	56.2	16.6	50.3
N13	Daur	104.1	34.8	121.3	143.7	36.2	50.4	17.3	50.6
N14	Yi	89.6	30.7	128.3	142.8	38.1	51.3	17.1	56
N15	Kirgiz	93.7	35.7	123.4	141.2	38.7	57.6	19.6	51.5
N16	Jingpo	102.72	35.84	123.74	139.53	38.94	51.87	18.22	53.32
N17	Hezhe	90.3	36.9	121.6	143.1	38.1	52.7	17.1	48.8
N18	Man	94.46	35.88	125.34	144.85	37.36	53.13	18.77	50.94
N19	Xibo	103.1	35.47	133.27	147.68	38.48	58.4	18.07	52.9
N20	Tajik	100.11	34.24	124.42	139.08	32.24	55.07	15.26	52.87
N21	Naxi	100.18	35.15	124.97	141.18	38.57	56.9	15.59	53.35
N22	Yugur	90.75	35.4	135.03	130.67	37.4	62.94	15.6	50.1
N23	Dong	96.03	33.22	113.68	131.62	38.85	49.08	19.04	50.38
N24	Miao	96.53	31.82	116.38	127.62	37.34	51.08	15.04	50.58
N25	Li	94.07	38.05	121.02	140.39	40.35	54.98	22.36	47.66
N26	Bao'an	86.39	33.33	128.63	140.33	35.41	56.06	15.15	50.14
N27	Dai	89.8	31.5	126.6	141.8	38.8	51.7	16.6	50.2
N28	Korean	98.51	33.71	125.47	142.98	37.51	55.62	18.81	50.98
N29	Zhuang	92	36.4	121.1	142.7	40.4	53.8	21.14	49.5
	F	2.352	3.07	1.202	0.724	6.168	0.732	2.92	0.863
	p	0.003**	0.000**	0.272	0.827	0.000**	0.818	0.000**	0.661

*$p < 0.05$

**$p < 0.01$

facial features of the warriors so far. This paper focused on the quantitative analysis of facial features of terracotta warriors through 58 samples randomly selected from 638 terracotta warriors in Pit No. 1 of Qin Shihuang Mausoleum. The anthropometric method is adopted to measure the physical head and facial dimensions of terracotta warriors with the support of high-resolution 3D scanning and modelling technology.

The results of MDS analysis reveal the great variabilities among the key facial features of warriors, which are like the variabilities of real humans. The result of comparison with 29 contemporary Chinese ethnic groups shows 75% of the key facial feature parameters of the terracotta warriors fall in the range of facial feature values of Chinese people. Statistically, there is no significant difference between terracotta warriors and contemporary Chinese people. All the results of ANOVA and cluster analysis indicate that the warriors were intended to be crafted as "real soldiers" or the substitute of a real army that served the first China emperor. This inference is more in line with the funeral culture at that time. The further statistical analysis of comparison with different

Table 7 Euclidean distance between terracotta warriors and different ethnic groups

	Terracotta army	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14
Terracotta army	0.000														
N1	21.198	0.000													
N2	24.212	4.699	0.000												
N3	28.723	9.320	7.053	0.000											
N4	16.347	16.448	17.643	21.639	0.000										
N5	21.737	8.229	9.196	13.977	12.971	0.000									
N6	31.809	14.425	11.682	6.793	23.903	18.339	0.000								
N7	22.675	5.656	5.991	10.634	17.940	9.358	15.691	0.000							
N8	26.359	9.709	8.010	10.675	14.841	7.895	13.505	11.303	0.000						
N9	20.899	6.567	7.113	11.021	15.661	8.333	14.546	5.798	11.036	0.000					
N10	26.340	6.874	7.900	10.290	21.873	11.764	15.359	6.405	12.532	9.443	0.000				
N11	25.638	17.512	17.985	18.411	13.738	14.648	18.513	18.958	13.877	15.033	20.458	0.000			
N12	20.802	12.164	12.495	17.875	11.039	6.155	21.700	13.358	10.548	12.392	16.609	16.963	0.000		
N13	19.843	14.356	15.433	17.920	6.653	10.321	20.497	16.144	11.779	13.558	19.450	10.103	10.683	0.000	
N14	25.642	8.308	8.172	10.740	19.297	12.676	15.636	7.202	11.008	11.616	8.137	20.509	16.041	17.621	0.000
N15	24.212	9.178	7.229	13.305	17.528	9.418	17.818	7.310	10.547	10.096	11.195	21.172	10.231	16.806	9.837
N16	16.418	12.276	14.539	17.358	8.442	10.899	20.280	13.542	13.463	11.063	16.921	11.421	13.096	6.651	15.476
N17	24.230	6.305	5.174	5.655	17.718	10.337	9.703	9.260	9.269	7.600	10.315	15.983	13.800	14.404	11.735
N18	20.471	4.780	5.932	10.327	13.488	6.116	15.228	6.749	8.504	6.362	10.193	15.578	9.025	11.082	9.783
N19	16.452	14.824	17.099	23.153	13.769	11.161	27.928	14.758	17.480	15.258	18.197	22.222	9.904	15.351	17.738
N20	22.692	11.829	13.730	16.300	13.019	8.056	19.488	12.814	10.681	10.844	13.781	9.871	12.264	9.701	14.616
N21	17.667	9.533	11.606	16.260	10.476	7.167	19.418	10.469	11.074	8.048	13.388	12.906	10.280	9.678	13.650
N22	28.340	17.423	19.978	22.029	28.713	19.608	26.217	16.405	23.478	17.410	13.915	26.779	24.816	26.433	19.720
N23	28.631	18.939	18.889	16.135	21.016	20.247	14.901	19.598	18.240	16.493	21.064	12.809	24.133	16.836	20.671
N24	30.280	19.916	20.531	18.274	23.127	20.870	17.728	20.567	19.320	17.966	20.706	14.016	25.669	18.863	21.355
N25	20.889	10.130	10.532	11.629	16.979	12.113	14.460	10.711	14.373	6.628	14.082	15.752	15.231	13.951	15.768
N26	28.554	8.268	8.419	9.690	23.517	12.417	14.975	8.241	12.608	11.046	3.381	21.494	17.421	20.454	9.564
N27	25.563	6.160	5.505	7.061	19.175	10.624	12.894	6.553	9.339	9.432	7.545	19.013	14.982	16.006	6.254
N28	19.277	8.139	9.464	13.985	11.364	4.642	18.164	8.014	9.611	6.386	12.220	13.874	8.306	9.041	11.984
N29	22.002	7.957	7.046	8.578	16.635	11.210	11.808	8.553	11.738	5.884	12.172	16.210	14.076	13.970	12.657

Table 7 (continued)

	N15	N16	N17	N18	N19	N20	N21	N22	N23	N24	N25	N26	N27	N28	N29
Terracotta army															
N1															
N2															
N3															
N4															
N5															
N6															
N7															
N8															
N9															
N10															
N11															
N12															
N13															
N14															
N15	0.000														
N16	16.543	0.000													
N17	11.501	13.992	0.000												
N18	8.138	10.447	6.595	0.000											
N19	13.816	14.162	19.324	13.382	0.000										
N20	15.664	8.610	13.687	10.713	14.855	0.000									
N21	12.959	6.597	12.513	8.857	11.330	7.022	0.000								
N22	21.996	22.172	21.133	20.395	21.925	19.199	18.683	0.000							
N23	24.072	15.248	16.150	18.427	28.125	16.993	17.938	26.372	0.000						
N24	25.758	16.471	18.496	20.400	28.524	16.182	18.040	23.336	6.915	0.000					
N25	14.327	12.193	7.902	8.912	18.774	14.409	12.126	20.797	14.610	17.772	0.000				
N26	12.024	18.630	10.452	11.358	19.759	15.061	15.126	14.459	21.635	21.105	14.929	0.000			
N27	9.951	14.543	7.733	7.821	18.060	13.758	12.734	18.449	18.033	18.868	12.126	7.339	0.000		
N28	9.952	7.687	10.446	5.554	10.954	7.963	5.206	19.253	17.872	19.002	9.857	13.519	10.293	0.000	
N29	11.354	12.697	5.183	6.805	18.515	14.446	12.014	21.562	15.298	18.610	4.315	13.020	9.380	9.385	0.000

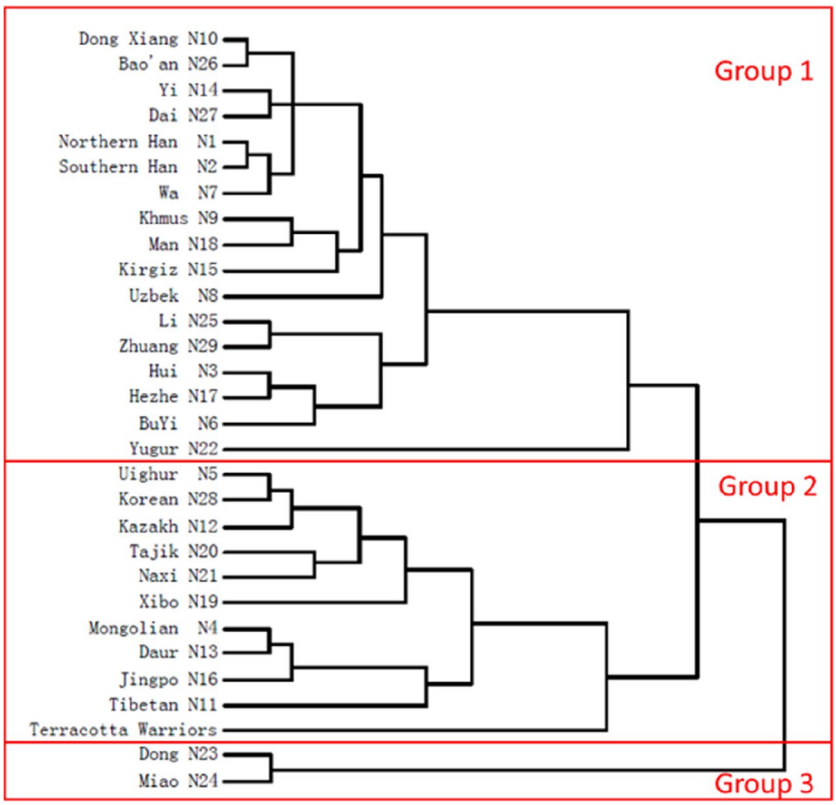

Fig. 16 Cluster analysis results

Chinese ethnic groups reveals that the facial features of terracotta warriors are more alike to those of northern and western Chinese populations. That means we could view the warriors as 3D portraits of Qin People. Therefore, the analysis results of similarities/differences could provide a further clue to explore the relationship between Qin people and contemporary Chinese people. For example, it could be used as clues to explore which Chinese ethnic groups could originate from Qin people, or where the Qin people migrated later.

However, there are still some challenges that need further research. The terracotta warriors were actually a

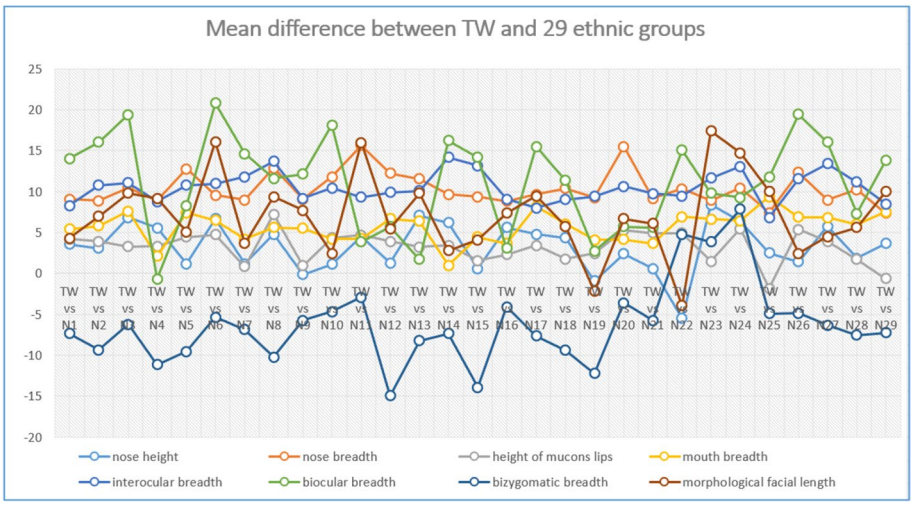

Fig. 17 Mean difference between TW and 29 ethnic groups

Table 8 ANOVA results (TW for the short name of terracotta warriors)

GROUP	Biocular breadth	Interocular breadth	Morphological facial length	Bizygomatic breadth	Nose breadth	Nose height	Height of mucons lips	Mouth breadth
TW vs. N1	●	●	○	●	●	●	●	●
TW vs. N2	●	●	●	●	●	●	●	●
TW vs. N3	●	●	●	●	●	●	●	●
TW vs. N4	○	●	●	●	●	●	●	○
TW vs. N5	●	●	○	●	●	○	●	●
TW vs. N6	●	●	●	●	●	●	●	●
TW vs. N7	●	●	○	●	●	○	○	●
TW vs. N8	●	●	●	●	●	●	●	●
TW vs. N9	●	●	●	●	●	○	○	●
TW vs. N10	●	●	○	○	●	○	●	●
TW vs. N11	○	●	●	○	●	●	●	●
TW vs. N12	●	●	○	●	●	○	●	●
TW vs. N13	○	●	●	●	●	●	●	●
TW vs. N14	●	●	○	●	●	●	●	○
TW vs. N15	●	●	○	●	●	○	○	●
TW vs. N16	○	●	●	○	●	●	○	●
TW vs. N17	●	●	●	●	●	●	●	●
TW vs. N18	●	●	○	●	●	●	○	●
TW vs. N19	○	●	○	●	●	○	●	●
TW vs. N20	●	●	○	○	●	○	●	●
TW vs. N21	●	●	○	●	●	○	●	●
TW vs. N22	●	●	○	●	●	●	●	●
TW vs. N23	●	●	●	○	●	●	○	●
TW vs. N24	●	●	●	●	●	●	●	●
TW vs. N25	●	●	●	●	●	○	○	●
TW vs. N26	●	●	○	○	●	○	●	●
TW vs. N27	●	●	○	●	●	●	●	●
TW vs. N28	●	●	○	●	●	○	○	●
TW vs. N29	●	●	●	●	●	●	○	●

●Significant difference statistically; ○no significant difference statistically

kind of art, after all, made from clay and had been buried underground for over 2200 years. It is still unclear how they were deformed during the production procedure and the long time of being buried underground. This might lead that the measurement results of facial features are not the real values when. terracotta warriors were shaped originally from clay. In this research, this kind of effect is not yet considered in the measurement result. It could cause statistically significant differences between the warriors and the contemporary Chinese population. However, the difference might be caused by the possible variation of facial features contemporary Chinese population due to climate change and dietary changes. Therefore, there are still more facts behind the realism of terracotta warriors to be revealed with more archaeological material and analysis.

Abbreviations

3D: Three dimensional; MDS: Multidimensional scaling analysis; ANOVA: Analysis of variance; BC: Before Christ; SIAATQ: Shaanxi Institute of Archaeology and Archaeological Team of Qinshihuangling; UNESCO: United Nations Educational, Scientific and Cultural Organization; HBR: Head to body ratio; DS: Down's syndrome; OAE: Ohr-Augen-Ebene; K–S: Kolmogorov–Smirnov; SPSS: Statistical Package for the Social Sciences; SAS: Statistical Analysis Software; TW: Terracotta warriors.

Acknowledgements

We are grateful to Qinshihuang Mausoleum Museum for sample data support. We would also like to thank Xin Zheng and Xuehui Yan for their help in data collection, as well as Shuo Yang and Zheng Yu for their useful suggestions.

Authors' contributions

YH conceived the presented idea and wrote the manuscript. DL performed Data collections. JW designed and conducted the analysis process. MH, SL, XL and LZ verified the analytical methods and supervised the findings of the work. All authors read and approved the final manuscript.

Funding
This research was supported by the National Cultural Heritage Administration (2020ZCK208) and The National Key Research and Development Program of China (2019YFC1520804).

Availability of data and materials
All data generated or analyzed during this study are included in this published article.

Declarations

Competing interests
The authors declare that they have no competing interests.

Author details
[1]School of Geomatics and Urban Spatial Informatics, Beijing University of Civil Engineering and Architecture, Beijing 100044, China. [2]Key Laboratory for Architectural Heritage Fine Reconstruction & Health Monitoring, Beijing 100044, China. [3]Department of Key Scientific Research Base of Ancient Polychrome Pottery Conservation, Emperor Qinshihuang's Mausoleum Museum, Xian 710600, Shaanxi, China. [4]The First Institute of Photogrammetry and Remote Sensing, Ministry of Natural Resources, Xian 710600, Shaanxi, China. [5]Department of Civil Engineering, Ryerson University, Toronto, ON M5B 2K3, Canada.

Received: 8 October 2021 Accepted: 4 February 2022
Published online: 21 March 2022

References

1. SIAATQ (Shaanxi Institute of Archaeology and Archaeological Team of Qinshihuangling). Excavation report on Pit 1 of the Qin terracotta warriors and horses 1974–1984 (Qinshihuang bingmayong keng yihaokeng fajue baogao). Beijing: Cultural Relics Press; 1988.
2. Yuan Z. Qinshihuang ling bingmayong yan jiu [Research on the terracotta warriors and horses from the Emperor Qin Shihuang's tomb complex]. Beijing: Cultural Relics Press; 1990.
3. Yuan Z. Qin shi huang ling de kao gu fa xian yu yan jiu [Archaeological discoveries and research on the Emperor Qin Shihuang's mausoleum]. Xi'an: Shaanxi People Press; 2002.
4. Fei Y. The significance of the discovery of terracotta warriors and horses to the study of ancient military and sculpture art. Comput Study Cult Innov. 2017:20–1.
5. Li XJ, Bevan A, Martinón-Torres M, Rehren T, Cao W, Xia Y, et al. Crossbows and imperial craft organisation: the bronze triggers of China's terracotta army. Antiquity. 2014;88:126–40.
6. He X. Inheritance, integration and the crystallization of the spirit of the times—also on the artistic origin of the realism of the terracotta warriors. Wenbo. 1987;1:51–4.
7. Cui B. On the realism and cultural connotation of the caly figures in Qin dynasty. Master Thesis. Jinan: Shandong University; 2009.
8. Nickel L. The first emperor and sculpture in China. Bull Sch Orient Afr Stud. 2013;76:413–47.
9. Kesner L. Likeness of no one: (re)presenting the first emperor's army. Art Bull. 1995;77:115–32.
10. Jarus O. Terracotta warriors: an army for the afterlife. 2016. https://www.livescience.com/25510-terracotta-warriors.html. Accessed 21 Dec 2021.
11. Quinn P, Yang Y, Xia Y, Li X, Ma S, Zhang S, et al. Geochemical evidence for the manufacture, logistics and supply-chain management of Emperor Qin Shihuang's terracotta army, China. Archaeometry. 2021;63:40–52.
12. Bevan A, Li X, Martinón-Torres M, Green S, Xia Y, Zhao K, et al. Computer vision, archaeological classification and China's terracotta warriors. J Archaeol Sci. 2014;49:249–54.
13. Komlos J. The size of the Chinese terracotta warriors-3rd century BC. Antiquity (Project gallery). 2003;77(296).
14. Lacruz RS, Stringer CB, Kimbel WH, Wood B, Harvati K, O'Higgins P, et al. The evolutionary history of the human face. Nat Ecol Evol. 2019;3:726–36.
15. Pan L, Wei D, Wu X. Latitudinal and climatic distributions of 3D craniofacial features among Holocene populations. Sci China Earth Sci. 2014;44(08):1844–53.
16. Richmond S, Howe LJ, Lewis S, Stergiakouli E, Zhurov A. Facial genetics: a brief overview. Front Genet. 2018;9:462.
17. Cole JB, Manyama M, Larson JR, Liberton DK, Ferrara TM, Riccardi SL, et al. Human facial shape and size heritability and genetic correlations. Genetics. 2017;205:967–78.
18. Hou M, Yang S, Hu Y, Wu Y, Jiang L, Zhao S, Wei P. Novel method for virtual restoration of cultural relics with complex geometric structure based on multiscale spatial geometry. ISPRS Int J Geo Inf. 2018;7(9):353. https://doi.org/10.3390/ijgi7090353.
19. Hirst CS, White S, Smith SE. Standardisation in 3D geometric morphometrics: ethics, ownership, and methods. Archaeologies. 2018;14:272–98.
20. Zhao S, Hou M, Hu Y, Zhao Q. Application of 3D model of cultural relics in virtual restoration. Int Arch Photogram Remote Sens Spatial Inform Sci. 2018;42:2401–5.
21. Horn F. Virtual colour reconstruction performed on the 3D model of a selected figure from the terracotta army. 2006. https://www.ar.tum.de/fileadmin/w00bfl/rkk/media_rkk/downloads/JB_2006_Band3_klein.pdf. Accessed 21 Dec 2021.
22. Wilkinson CM, Roughley M, Moffat RD, Monckton DG, MacGregor M. In search of Robert Bruce, part I: craniofacial analysis of the skull excavated at Dunfermline in 1819. J Archaeol Sci Rep. 2019;24:556–64.
23. FARO. FARO edge and FARO laser ScanArmEdge manual; 2016. https://downloads.faro.com/index.php/s/N95m3Hi8LZQw4FP. Accessed 21 Dec 2021.
24. Zhao Z, Xiao W, Xia J, et al. The excavation of the Terracotta Army pit No. 1 of Emperor Qin Shihuang's Mausoleum in 2009–2011. Cult Relics. 2015;9:4–38.
25. Foat FWG. Anthropometry of Greek statues. J Hell Stud. 2015;35:225–59.
26. Siromoney G, Bagavandas M, Govindaraju S. An application of component analysis to the study of South Indian sculptures. Comput Humanit. 1980;14:29–37.
27. Mather G. Head-body ratio as a visual cue for stature in people and sculptural art. Perception. 2010;39:1390–5.
28. Starbuck JM. Quantitative evaluation of the facial morphology of a tolteca figurine from Mexico using geometric morphometric approaches. Int J Morphol. 2014;32:499–509.
29. Shao X. Anthropometric handbook. Shanghai: Shanghai Dictionary Press; 1985.
30. Fang F, Zhang W, Zhang W, et al. Study on standards of the human body measurement. J Donghua Univ (Nat Sci Ed). 2005;01:132–8.
31. Fagertun J. Face recognition. Master Thesis. Kongens Lyngby: Technical University of Denmark; 2005.
32. Fagertun J, Harder S, Rosengren A, Moeller C, Werge T, Paulsen RR, et al. 3D facial landmarks: inter-operator variability of manual annotation. BMC Med Imaging. 2014;14:35.
33. Young JW. Head and face anthropometry of adult US civilians. Fort Belvoir: Defense Technical Information Center; 1993.
34. China Standard. GB/T 3975-1983 anthropometric terminology. Beijing: China Standard Press; 1984.
35. China Standard. GB/T 5703-1985 anthropometric methods. Beijing: China Standard Press; 1986.
36. Han X, He X, Duan X, Zhang X, Su B, Jiang X, et al. Investigation on physical characteristics of man nationality in Jilin province. Acta Anthropol Sin. 1993. https://doi.org/10.16359/j.cnki.cn11-1963/q.1993.01.007.
37. Yu KL, Zheng LB, Li YL, Xi HJ, Lu SH, Zhang XH, et al. Differences of head-face morphological traits between southern and northern Chinese Han. Acta Anat Sin. 2016;47(03):404–8.
38. Zheng L, Zhu Q, Wang Q, Gao Q, Li C, Li W, et al. Study on physical characteristics of Ningxia Hui nationality. Acta Anthropol Sin. 1997. https://doi.org/10.16359/j.cnki.cn11-1963/q.1997.01.002.
39. Zhu Q, Liu W, Li Z, Zhang J, Qingele Z, Zhang X. Physique, body type of Mongols and their changes in the past more than half a century. Acta Anthropol Sin. 1993;04:347–56.

40. Ai Q, Xiao H, Zhao J, Xu Y, Shi F. Study on physical characteristics of Uighur nationality. Acta Anthropol Sin. 1993. https://doi.org/10.16359/j.cnki.cn11-1963/q.1993.04.007.
41. Zheng LB, Zhang SL, Lu SH, Zhao Z, Suo LY, Yang JH. A study of the physical characteristics of the Bouyei nationality. Acta Anthropol Sin. 2005. https://doi.org/10.16359/j.cnki.cn11-1963/q.2005.02.004.
42. Zheng LB, Lu SH, Yu HX, Liu HP. Physical characteristics of Wa nationality. Acta Anthropol Sin. 2007. https://doi.org/10.16359/j.cnki.cn11-1963/q.2007.03.001.
43. Zheng L, Cui J, Lu S, Li S, Gu L. A study on the physical characteristics of Uzbek nationality. Acta Anthropol Sin. 2004. https://doi.org/10.16359/j.cnki.cn11-1963/q.2004.01.005.
44. Zheng LB, Lu SH, Chen YY, Yu HX, Liu HP. Physical characteristics of Chinese Kemu people. Acta Anthropol Sin. 2007. https://doi.org/10.16359/j.cnki.cn11-1963/q.2007.01.005.
45. Dai Y, Yang D. Study on physical characteristics of Dongxiang nationality in Gansu province. Acta Anthropol Sin. 1991. https://doi.org/10.16359/j.cnki.cn11-1963/q.1991.02.005.
46. Hai X, Dai Y. Study on the head and face characteristics of Chinese Tibetans. Health Vocat Educ. 2005;23(19):120–3.
47. Cui J, Shao X, Wang J, et al. Investigation on the physical characteristics of Kazak nationality in Xinjiang. Acta Anthropol Sin. 1991. https://doi.org/10.16359/j.cnki.cn11-1963/q.1991.04.005.
48. Shi Q, Hu J, Yang H. Investigation of the physical characteristics of Daur nationality in Heilongjiang province. J Anthropol. 1983. https://doi.org/10.16359/j.cnki.cn11-1963/q.1983.01.007.
49. Pang Z, Li P, Liang M, Sun S, Li Q, Ou Y, et al. A physical survey of Miao and Yi Nationalities in de'e. Guangxi Acta Anthropol Sin. 1987. https://doi.org/10.16359/j.cnki.cn11-1963/q.1987.04.008.
50. Shao X, Chui J, Zhu X, Yang Z, Wu G, Zhao J, et al. Physical characteristics of Kirgiz nationality in Tekes county. Xinjiang Acta Anthropol Sin. 1987. https://doi.org/10.16359/j.cnki.cn11-1963/q.1987.04.007.
51. Li M, Yu F, Liu G, et al. Physical characteristics of Jingpo nationality in Yunnan province. Acta Anthropol Sin. 1989. https://doi.org/10.16359/j.cnki.cn11-1963/q.1989.01.002.8-16.
52. Shi Q, Hu J, Zhao G. Physical characteristics of Hezhe nationality. Acta Anthropol Sin. 1987. https://doi.org/10.16359/j.cnki.cn11-1963/q.1987.04.009.
53. Shao X, Wang D, Cui J, Zhu X, Zhao W, Gu L, et al. Investigation on the physical characteristics of Xibo nationality in Qapqal, Xinjiang. Acta Anthropol Sin. 1984. https://doi.org/10.16359/j.cnki.cn11-1963/q.1984.04.008.
54. Shao X, Cui J, Wang J, Yang G. Physical characteristics of Tajik nationality in Tashkurgan, Xinjiang. Acta Anthropol Sin. 1990. https://doi.org/10.16359/j.cnki.cn11-1963/q.1990.02.003.
55. Liu G, Yu F, Li M, Gha F. Physical characteristics of Naxi nationality in Yunnan province. Acta Anthropol Sin. 1992. https://doi.org/10.16359/j.cnki.cn11-1963/q.1992.01.003.
56. Dai Y, Ding J, Zou Z. A preliminary study on the physical characteristics of Yugur nationality in Gansu province. Acta Anthropol Sin. 1987;3:227–35. https://doi.org/10.16359/j.cnki.cn11-1963/q.1987.03.010.
57. Pi J, Wu Y, She C. Analysis of the physical characteristics of the head and face of Dong nationality adults in Hunan province. Anat Study. 2003;25(3):221–3.
58. Pi J, Wu Y, Lei M. Measurement and analysis of head and face physique of Miao nationality in Western Hunan. Ergonomics. 2007. https://doi.org/10.13837/j.issn.1006-8309.2007.04.001.
59. Zhang Z, Zhang J. Anthropological studies on LI nationality in Hainan island, China. Acta Anthropol Sin. 1982;1:53–71.
60. Yang D, Dai Y. Physical characteristics of Bao'an nationality in Gansu province. Acta Anthropol Sin. 1990. https://doi.org/10.16359/j.cnki.cn11-1963/q.1990.01.010.
61. Zhang X, Zheng L, Yu K, Bao J, Li Y, Tian J, et al. Variation of head and facial morphological characteristics with increased age of Xishuangbanna Dai. J Nanjing Norm Univ (Nat Sci Ed). 2016;39:79–85.
62. Jin C, Jin D, Piao X. Anthropological characteristics of Korean nationality in Jilin Province. Med J Yanbian Univ. 1997;02:4–7.
63. Zhang Z, Zhang J. Physical characteristics of Zhuang nationality in Guangxi. Acta Anthropol Sin. 1983. https://doi.org/10.16359/j.cnki.cn11-1963/q.1983.03.007.
64. Massey FJ. The Kolmogorov–Smirnov test for goodness of fit. J Am Stat Assoc. 1951;46:68–78.
65. Park HM. Univariate analysis and normality test using SAS, Stata, and SPSS. Bloomington: The University Information Technology Services, Indiana University; 2008.
66. Lilliefors HW. On the Kolmogorov–Smirnov test for normality with mean and variance unknown. J Am Stat Assoc. 1967;62:399–402.
67. Li Y. Cluster analysis and principal component analysis of head and face indexes of rural Han males in China. J Anat. 2018;41(02):190–5.
68. Li S, Zheng L. Cluster analysis on cranio facialpart index from thirty ethnic groups in China. J Inn Mong Norm Univ (Nat Sci Chin Ed). 2005:365–8.
69. Li Z, Duan X, Wang C. Cluster analysis of facial geometric features of six ethnic groups in China. J Dalian Univ Natl. 2015. https://doi.org/10.13744/j.cnki.cn21-1431/g4.2015.01.019.
70. Liu R. SPSS statistical software. Beijing: China Press of Traditional Chinese Medicine; 2007.
71. Fang K. Cluster analysis (I). Pract Underst Math. 1978;01:66–80.
72. Yin X. Econometrics: principles and operations. Chongqing: Chongqing University Press; 2009.
73. Saeed N, Nam H, Haq MIU, Muhammad Saqib DB. A survey on multidimensional scaling. ACM Comput Surv. 2018;51:47.
74. Jaworska N, Chupetlovska-Anastasova A. A review of multidimensional scaling (MDS) and its utility in various psychological domains. Tutor Quant Methods Psychol. 2009;5:1–10.
75. Zhang J, Wu X, Li L, Jin L, Li H, Tan J. Cranial non-metric evidence for population admixture between east and west Eurasia in Bronze Age, Southwestern Xinjiang. Acta Anthropol Sin. 2011;30(04):379-404. https://doi.org/10.16359/j.cnki.cn11-1963/q.2011.04.006
76. Yates F, Fisher R. Statistical methods for research workers. Edinburgh: Oliver & Boyd; 1925.
77. Pasupa K, Sunhem W, Loo CK. A hybrid approach to building face shape classifier for hairstyle recommender system. Expert Syst Appl. 2018;120:14–32.
78. Givens G, Beveridge J, Draper B, Bolme D. A statistical assessment of subject factors in the PCA recognition of human faces. In: 2003 conference on computer vision and pattern recognition workshop. Madison: IEEE; 2003. p. 96.
79. Holton NE, Alsamawi A, Yokley TR, Froehle AW. The ontogeny of nasal shape: an analysis of sexual dimorphism in a longitudinal sample. Am J Phys Anthropol. 2016;160:52–61.
80. Stansfield E, Mitteroecker P, Vasilyev SY, Vasilyev S, Butaric LN. Respiratory adaptation to climate in modern humans and Upper Palaeolithic individuals from Sungir and Mladeč. Sci Rep. 2021;11:7997.

Publisher's Note