Decoding the shoes of Terracotta Warriors: in terms of restoration technology and functional performance

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ABSTRACT – REZUMAT

Decoding the shoes of Terracotta Warriors: in terms of restoration technology and functional performance

The shoes of the Terracotta Warriors hold significant historical and cultural value as an important legacy of ancient Chinese shoemaking craftsmanship. However, there is a dearth of research on terracotta shoes. Therefore, this study aimed to restore the Terracotta Warrior's shoes from the perspectives of clothing engineering and archaeology, and then to assess the critical function of the restored shoes. Finally, we will explore why the soldiers of the Qin Dynasty (221–206 BC) were so successful in the military. In the restoration process, we utilized Augmented Reality ranging technology to conduct field investigations in museums, obtaining the basic form of the shoe of the kneeling archer figurine No.05438, and based on this, we studied its techniques and materials. Further, a quantitative analysis of the structural functionality of the Qin Dynasty shoes was carried out. Results show that: (1) the shoe soles of the Terracotta Warriors were adorned with neatly arranged circular patterns; the shoe sole was divided into three sections, with a ratio of 8:13:6 among the three sections; (2) the production technique of the shoe sole was consistent with the Thousand-layer sole, and the material used was red ramie; (3) we compared the replica shoes with two similar modern shoes and found that the replica shoes not only exhibited excellent flexibility but also demonstrated better slip resistance in wet conditions. Overall, we successfully reconstructed the shoe and evaluated its functionality using advanced archaeological techniques. Our finding unveiled notable advantages in flexibility and slip resistance in the Terracotta Warrior's shoes, enhancing our understanding of ancient shoes. Additionally, this study also provides valuable practical experience and methodology for archaeology in restoring ancient shoes.

Keywords: *ergonomics, Qin Dynasty shoes, recovery technique, shoe material, shoe's flexibility, slip resistance*

Decodificarea încălţămintei armatei „de teracotă" în ceea ce privește tehnologia de restaurare și performanța funcțională

Încălţămintea armatei „de teracotă" are o valoare istorică și culturală semnificativă, ca o moștenire importantă a măiestriei antice chineze în confecţionarea pantofilor. Dar există o lipsă a studiilor în ceea ce priveşte încălţămintea armatei „de teracotă". Prin urmare, acest studiu și-a propus să restaureze încălţămintea armatei „de teracotă" din perspectiva ingineriei îmbrăcămintei și a arheologiei și apoi să evalueze funcția critică a pantofilor restaurați. În cele din urmă, a fost explorat motivul pentru care soldații dinastiei Qin (221–206 î.Hr.) au avut atât de mare succes în armată. În procesul de restaurare, a fost utilizată tehnologia pe baza realităţii augmentate pentru a efectua investigații de teren în muzee, obținându-se forma de bază a încălţămintei figurinei de arcaș stând în genunchi nr.05438 și, pe baza acesteia, au fost studiate tehnicile și materialele din care aceasta a fost confecţionată. În plus, a fost efectuată o analiză cantitativă a funcționalității structurale a încălţămintei dinastiei Qin. Rezultatele arată că: (1) tălpile încălţămintei purtate de armata „de teracotă" erau împodobite cu modele circulare ordonate; talpa a fost împărțită în trei secțiuni, cu un raport de 8:13:6 între cele trei secțiuni; (2) tehnica de producție a tălpii de încălțăminte a fost în concordanță cu cea a tălpii cu o mie de straturi, iar materialul folosit a fost ramia de culoare roşie; (3) au fost comparate copiile cu doi pantofi moderni similari și am constatat că aceştia nu numai că au prezentat o flexibilitate excelentă, ci au demonstrat şi o rezistență superioară la alunecare în condiții de umiditate. În general, a fost reconstuit cu succes pantoful și a fost evaluată funcționalitatea acestuia folosind tehnici arheologice avansate. Descoperirea noastră a dezvăluit avantaje importante în ceea ce priveşte flexibilitatea și rezistență la alunecare a încălţămintei purtate de armata „de teracotă", îmbunătățind înțelegerea noastră despre încălţămintea din antichitate. În plus, acest studiu oferă, de asemenea, experiență practică și o metodologie valoroasă pentru arheologie în restaurarea pantofilor antici.

Cuvinte-cheie*: ergonomie, încălţăminte aparţinând dinastiei Qin, tehnică de restaurare, materialul pantofilor, flexibilitatea pantofilor, rezistenţa la alunecare*

INTRODUCTION

Historical and cultural heritage serves as a bridge connecting the ancient and modern world, providing a key for contemporary individuals to explore ancient civilizations [1]. This heritage possesses significant historical, scientific, cultural, and artistic value, reflecting the lifestyle, social systems, and economic development of ancient societies [2]. As one of the precious cultural heritages, extensive research has been conducted on the armour techniques and structure of the Terracotta Warriors both domestically and internationally. Since the majority of the warriors are in a standing position, making it difficult to observe their shoe soles, the shoes of the Terracotta Warriors have been rarely considered. However, the shoes hold a significant position in Terracotta Warrior's archaeological research. They serve as important evidence of the shoes worn and equipped by the Qin Dynasty Warriors, as well as crucial samples for studying ancient textiles. Through the study of Terracotta Warrior's shoes, we can not only understand the ancient Chinese shoemaking techniques and material usage, providing a scientific basis for the protection and restoration of the Terracotta Warriors, but also gain insights into the military system, warfare technology, and the soldiers' living conditions during the Qin Dynasty. This research is invaluable in promoting our understanding and appreciation of ancient culture. Therefore, the study of Terracotta Warrior's shoes should not be overlooked.

Currently, research on the shoes of the Terracotta Warriors primarily focuses on analysing their cultural value and discussing their structural functionality. Miao et al. [3], proposed that the shoes of the Terracotta Warriors represented a "pragmatic culture" and possessed practicality and convenience. Yue et al. [4] suggested that the shoes of the Terracotta Warriors, as the oldest and most enduring sewn shoes with Thousand-layer soles (TLS), affirmed the significance and value of restoring the shoes, which helped to further study the origins and development of shoes in China. The "Seal Examination Style" from "Shuihudi Qin bamboo texts" recorded the pattern on the shoe sole of Qin people's shoes as sparse in the middle and dense at both ends, which matched the shoe sole mechanics during wear and the importance of durability. However, the functional performance of these shoes had not been quantitatively studied. Therefore, it is necessary to restore the shoe soles of the Terracotta Warriors based on literature and on-site investigations to conduct functional evaluations.

Scientific archaeology has emerged as a significant field of research in the restoration of shoes. Initially, researchers relied on unearthed relics to make basic inferences about their shoes. For example, Kochkina et al. [5] examined the manufacturing techniques and origins of funeral leather shoes in the Malay Liang Zhan Tomb Site, while Stevens et al. [6] studied the structure, size, and social indicators of wearers, such as their class, gender, and occupation, in 19th-century Boston shoes. With advancements in scientific technology, new techniques have been developed to preserve cultural heritage. More researchers are now utilizing methods like digital reconstruction to achieve shoe restoration. For instance, Abdullin et al. [7] developed a system for restoring fibrous structures, enabling the reconstruction of shoes made from flexible leather and birch bark, which were popular from the 17th to the 19th century. From a modern biomechanical perspective became another protocol to evaluate the structure and functionality of artifacts. Volken et al. [8] analysed the plantar pressure distribution to determine why a 15th-century military shoe could be used for military purposes. Moskvin et al. [9] also utilized computer-aided technologies to analyse the physical, materials science, anatomical, and biomechanical aspects of the shoes and other garments worn by a German warrior from the 2nd to the 4th century AD, based on scientific data to prove their functionality. Huang et al. [10] employed modern techniques such as X-ray testing, multispectral photography,3D scanning, and high-definition photography to successfully restore jade shoes from the Han Dynasty. These cases indicated that the restoration and quantitative analysis of the structure and functionality of ancient shoes are gradually becoming a powerful research tool, providing new insights into traditional archaeological artefacts. However, previous studies have not systematically examined the restoration, structure, and functionality of Terracotta Warriors' shoes.

Therefore, this study aimed to restore the Terracotta Warrior's shoes from the perspectives of clothing engineering and archaeology. The primary objective was to gain a deeper understanding of ancient craftsmanship, structure, and understanding of the functionality of shoes. In addition, our goal is to assess the critical function of the restored shoes and to decode why the soldiers in the Qin Dynasty were so successful in military exploits. According to this study, the producing techniques and technical plans of the Qin Terracotta Warrior's shoes, as well as physical restorations and modern functional evaluations will be studied. Our finding would reveal the exquisite craftsmanship and wisdom of ancient shoemaking, to shed light on the ancient people's understanding of the functional requirements of shoe soles.

METHODS

Restoration objects

The chosen target for restoration research was the kneeling archer figurine, labelled as 05438, which was unearthed from the eastern end of trench T21G18 in Pit2 [11]. Figure 1 exhibited minimal damage. It was depicted wearing a battle robe, draped

Fig. 1. Three-view of kneeling archer figurine in Sichuan Museum

with armour, and wearing square-toed shoes with upturned tips.

Restoration method

Shoe style

Based on the shoe information depicted on the kneeling archer figurine from the Qin Dynasty with the label 05438, we compared it with the shoes unearthed from the nearby Han Dynasty (206 BC–8 AD) at the Mawangdui site and concluded that the square-mouthed shallow shoes worn by the figurine did indeed exist [12]. These analyses and inferences would contribute to further research on the basic form and structure of the shoe.

Basic dimensions

To measure the dimensions of the shoe sole, we utilized an Augmented Reality (AR) rangefinder, which was a non-contact measurement tool based on structured light technology. This application is compatible with Apple iOS12 systems. It uses an invisible laser as a light source to emit encoded light patterns onto the object. By employing specific algorithms, it calculates the distortion of the returned encoded patterns, thereby obtaining the position and depth information of the object and achieving remote distance measurement [13]. The maximum depth range for recognition with this rangefinder was limited to 1.2 meters, therefore, the distance between the phone and the object being measured falls within this range while scanning [14]. The steps are shown below (figure 2):

Step 1. Open the rangefinder application.

Step 2. Keep your phone as parallel as possible to the object being measured and perpendicular to the ground. Slowly move the phone to locate the plane where the object is situated.

Step 3. When a measuring point appears on the plane, move the measuring point to the starting point of the object you want to measure and click the "+" button to begin the measurement.

Step 4. Move the measuring point to the end point of the object and click the "+" button to end the measurement. The length of the object will be displayed. The measurement accuracy of this rangefinder can range from 0.1 mm to 1 mm.

Restoration production

Firstly, based on the analysis of the extracted information from the selected kneeling archer figurine, the restored shoe details were determined based on the original state of the shoe sole. Secondly, through literature research and in-depth interviews [15], the traditional crafting techniques and materials used for making the shoe soles of Terracotta warriors were summarized and compiled. The overall restoration process began with a clothing engineering perspective, utilizing a two-dimensional sole pattern to create a three-dimensional object. The main steps were as follows (figure 3).

The production of the shoe sole included two main stages: paste preparation and sole fabrication, with the latter comprising six major steps:

Step 1: Paste preparation involves mixing wheat or corn flour with warm water at a ratio of 1:2, ensuring that the water temperature remains below 30 °C scale. The mixture is stirred thoroughly until it reaches a consistency resembling that of yoghurt. Next, the paste is rapidly and evenly spread onto a piece of cloth using a spatula before being left to dry in the sun. This serves as a backup for the subsequent steps.

Step 2: Sole fabrication. This step consists of six substeps: cutting the sole, glueing the sole, wrapping the sole, circling the sole, inserting the sole, and pounding the sole.

Cutting the sole: Based on the shoe's last, draw the sole pattern and leave a 2–3 cm margin on the edges for the upper part of the shoe. This will result in the final shoe pattern. Trace the left and right shoe patterns onto the previously prepared and dried linen cloth. Repeat the cutting process until the desired sole height is achieved.

Glueing the sole: According to the desired thickness of the sole, typically 1.5 cm, stack 5–7 layers of sole material together, forming a structure called “xian'er”.

Step 3: Wrapping the sole: Temporarily secure the sole material with sewing thread and then use the bias of the linen cloth to wrap the edges.

Step 4: Circling the sole: Use ramie to make a core and twist it into a rope. Sew a loop of twine along the

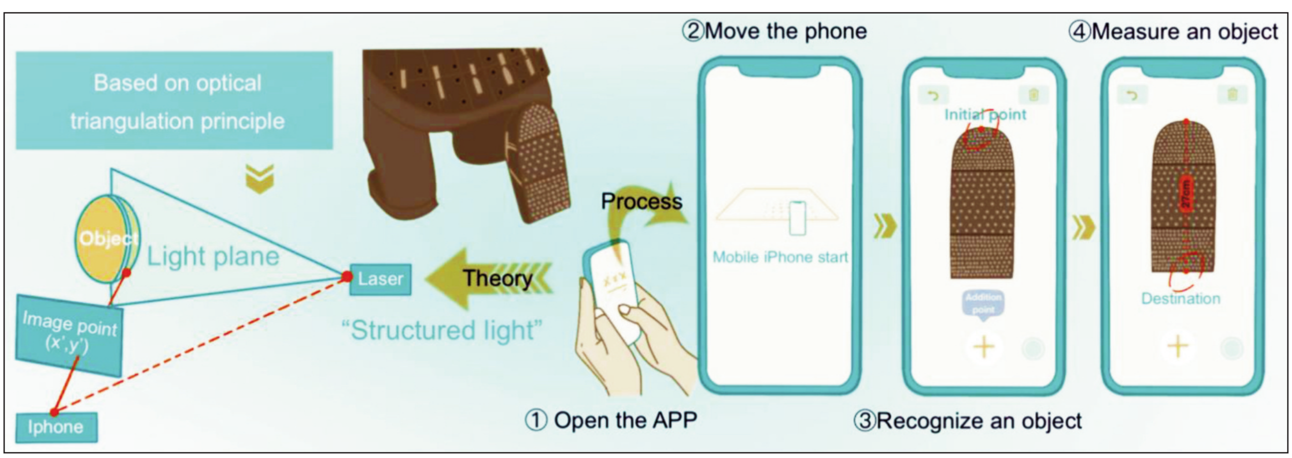


Fig. 2. Non-contact technology – AR distance measurement step diagram and scheme

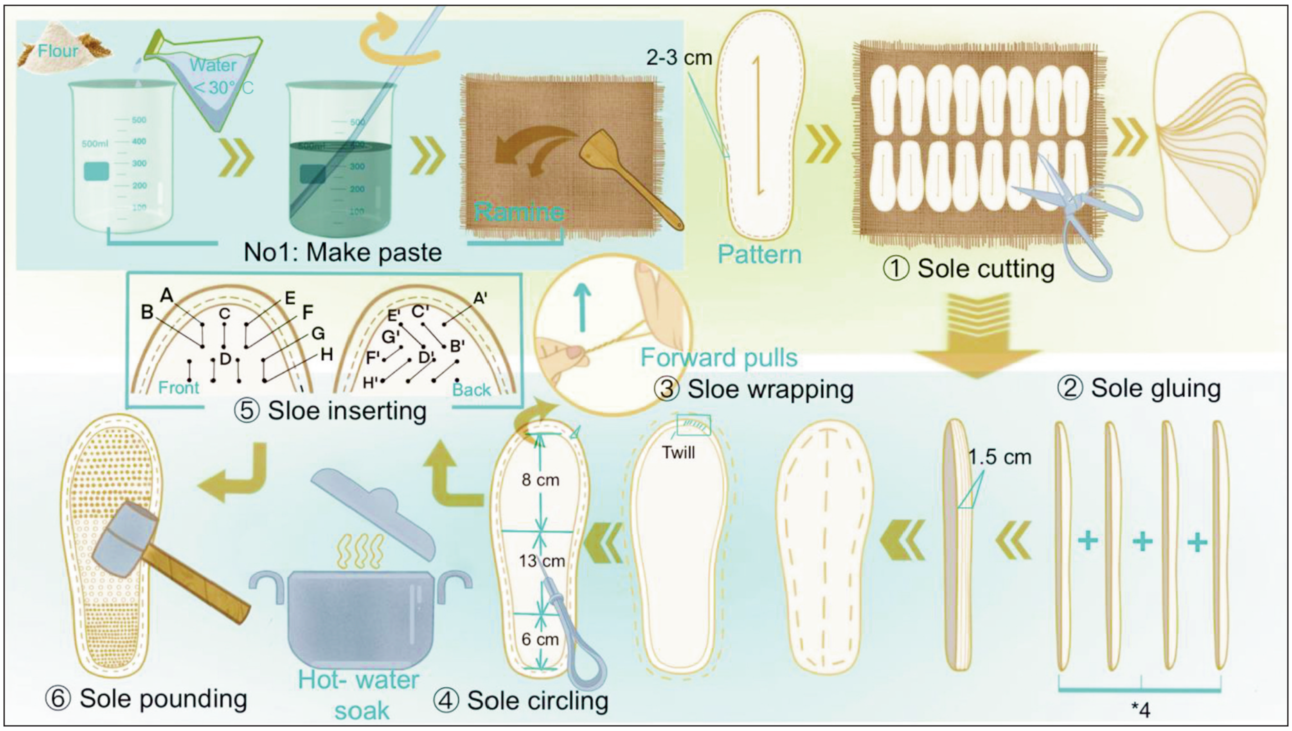


Fig. 3. Shoe sole manufacturing process flow

edge of the sole, spaced about 2 mm apart. Pay attention to ensure tight, neat, and consistent stitching, with stitches aligned horizontally and vertically. The stitches should be tight and evenly distributed. The method of twisting the hemp rope is done manually, as follows [16]:

Divide the ramie fibre into two strands and twist one strand forward on your leg until it becomes a tightly twisted cord. Use one hand to hold the twisted fibre in place.

Twist the other strand using the same method as above and place the two twisted strands together.

Twist forward with your hand and quickly pull it back, repeating this motion.

Step 5: Inserting the sole: Mark the needle holes on the stacked sole material and sew them together using the ramie rope. (Before sewing, the ramie rope can be soaked in wax water and then used. This makes it easier for the rope to pass through the 1.5 cm thick sole, improving efficiency). Use a clamp to secure the stacked sole material. Before each stitch, use an awl to create the needle holes and then pass the needle through.

Step 6: Pounding the sole: After soaking and steaming the stitched sole in hot water, use an iron hammer to flatten it. Finally, place it in a cool and well-ventilated area to air dry naturally, completing the production of the layered sole.

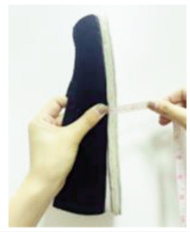
Assessing the key function of restored shoes

The shoes' basic function, slip resistance and flexibility decided the anti-slip ability and the comfort while walking. We contrasted the two properties of the restored TLS shoe (RTLS) and two modern TLS shoes (Zhuangyuan Orchid Cloth Shoes and Qinghong Hundred Years of Cloth Shoes), the similarities and differences among the three samples are summarized in table 1.

The slip resistance of the shoe sole was tested using a computerized slip resistance tester (model GT-7012-BEA). The principle of this system involves placing the sample on the testing interface, applying a specified force, and moving the plane relative to the sample horizontally or at a certain angle. The frictional force is measured and used to calculate the coefficient of friction. The coefficient of friction is used to evaluate the slip resistance of the shoe sole [17]. According to the formula $\mu = f/F$, the coefficient of friction is directly proportional to the frictional force. Therefore, a smaller coefficient of friction indicates poorer slip resistance, while a larger coefficient indicates better slip resistance. Three walking modes were simulated during the testing: forefoot, horizontal, and heel modes, which represented different walking states. Three tests were conducted using the same samples and modes under both dry and wet conditions, as shown in figure 4, *a*. The average values were calculated to represent the slip resistance performance of the samples.

The flexibility performance of the shoe sole was evaluated using a thin film pressure sensor. This device is suitable for measuring pressure, tension, pressure difference, and other physical quantities that can be converted into force [18]. The testing principle involves attaching the sensitive element of the thin film pressure sensor to the middle position of the heel of the shoe sole. The toe part of the shoe was fixed, and the heel of the sample was sequentially lifted to 45°, as shown in figure 4, *b*, to simulate the state of wearing the shoe and effectively evaluate the flexural

Table 1

<table>
<tr><td colspan="6">COMPARATIVE PLOTS OF SIMILARITIES AND DIFFERENCES FOR SAMPLES 1–3</td></tr>
<tr><th>Name</th><th>Stitch</th><th>Sewing methods</th><th>Thickness</th><th>Material</th><th>Sole pattern distribution</th></tr>
<tr><td>RTLS</td><td>Vertical seam stitching</td><td>Single needle Diamond shape</td><td>1.5 cm</td><td>Ramie</td><td>Dense in the front and back, sparse in the middle</td></tr>
<tr><td>ZOCS</td><td>Vertical seam stitching</td><td>Single needle Diamond shape</td><td>1.5 cm</td><td>Ramie</td><td>The outsole is evenly distributed</td></tr>
<tr><td>QHYOCS</td><td>Circular seam stitching</td><td>Circular single needle</td><td>1.5 cm</td><td>Cotton</td><td>The outsole is evenly distributed</td></tr>
<tr><th>No.</th><th colspan="2">The bottom view</th><th colspan="2">The side view</th><th>The front view</th></tr>
<tr><td>TWRS
(Sample 1)</td><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td>ZOCS
(Sample 2)</td><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td>QHYOCS
(Sample 3)</td><td colspan="2"></td><td colspan="2"></td><td></td></tr>
</table>

performance of the shoe sole. During the testing process, the force required to lift the heel of the shoe was recorded. A higher force indicated poorer flexural performance, while a lower force indicated better flexural performance. This process converted the change in weight into a change in pressure. Each sample was tested three times, and the average value was calculated to represent the flexural performance of the samples.

RESULT

Restoration of Terracotta Warrior's shoes

Based on the photographs taken on-site, we have completed the reconstruction of the two-dimensional image of the shoe sole. As shown in figure 5, *a*, the shoe sole was comprised of three areas: Area A, the forefoot region, with a length of 8 cm; Area B, the middle region, with a length of 13 cm; and Area C, the heel region, with a length of 6 cm. The width of the toe box was 11 cm, and the length of the shoe opening was 19.5 cm. The arrangement of stitch holes in different areas was as follows: Area A has the highest number of horizontal and vertical stitch holes, with 22 and 23 respectively. Area B had the lowest number of horizontal and vertical stitch holes, with 10/11 and 14 respectively. The patterns on the forefoot and heel areas are dense, while the patterns in the middle area are sparse. This pattern was the stitching line of

a *b*

Fig. 4. Chart of: *a* – slip resistance test; *b* – flexibility test

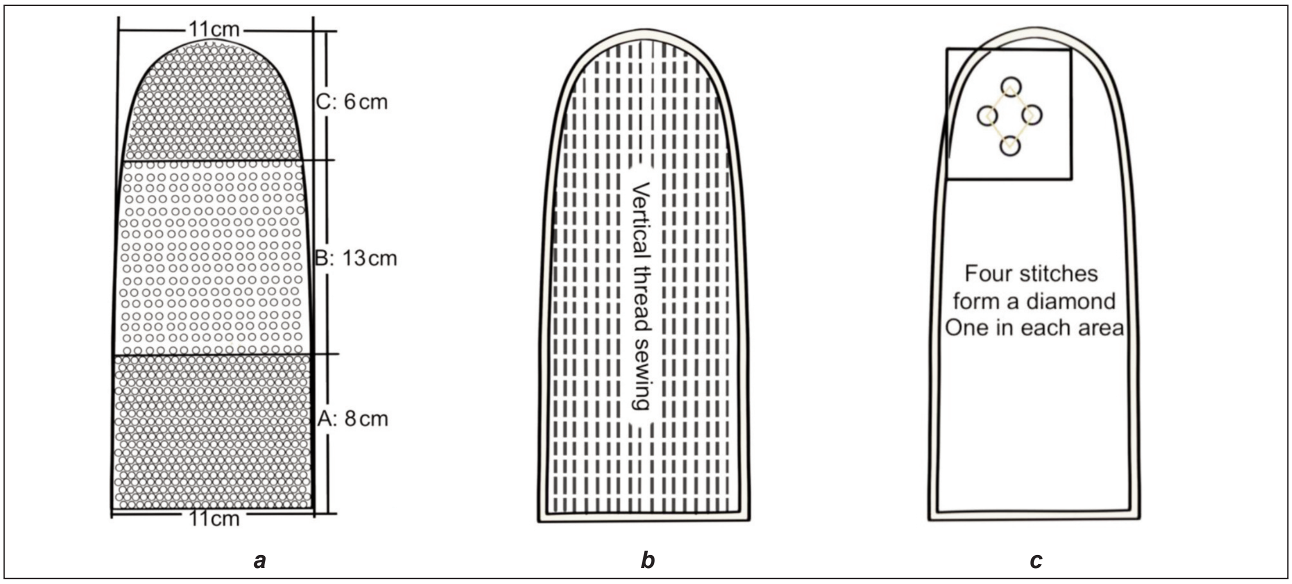


Fig. 5. Chart of: *a* – sole 2D reconstruction; *b* – vertical line stitch; *c* – single needle diamond stitch

sewing, which can be categorized into four types: horizontal lines, vertical lines, diagonal lines, and circular lines. In terms of stitching techniques, there were mainly two types of stitching techniques for the welt seam, namely, the "zaohua diamond" and the "single needle diamond". By comparing the pattern structure of the shoe sole model 05438 with the above techniques, we determined that the stitching method used was vertical line stitching (figure 5, *b*) and the stitching technique was the single needle diamond (figure 5, *c*).

The restoration results of Terracotta Warrior's shoes

Figure 6 shows the reconstructed shoe sole in both their front and back views, detailed images of the front, middle, and backline traces of the sole in both front and back views, as well as an image demo of Terracotta Warrior's recovered shoe sole and wear effect show picturenstrating the wearing effect.

Results of anti-slip performance

Based on the results of the coefficient of friction for the shoe sole in table 2, the following conclusions can be drawn: In a wet environment, sample 1 had the highest static coefficient of friction (SF) in both the horizontal and heel modes. Additionally, sample 3 exhibited the highest values for both the dynamic and static coefficients of friction (DF and SF), indicating better slip resistance. The difference in friction coefficients between sample 1 and sample 2 was not significant for the two media in all three modes. Furthermore, all three samples showed better slip resistance in wet conditions compared to dry conditions.

Results of flexibility performance

The minimum force required to lift sample 1 was 4.9 N, followed by sample 2 which required 7.2 N of force. Sample 3 required the highest force, which was 8.5 N. Based on this, we can conclude that Sample 1 (recovered shoes) was more prone to bending during walking, indicating better flexibility. This superior flexibility was reflected in improved

Fig. 6. Image of: *a* – Terracotta Warrior's shoe sole physical restoration; *b* – craftsmanship detail

Table 2

COMPARATIVE RESULTS OF SLIP RESISTANCE TEST												
No.	**Forefoot**				**Level**				**Heel**			
	Dry		**Damp**		**Dry**		**Damp**		**Dry**		**Damp**	
	DF	**SF**	**DF**	**SF**	**DF**	**SF**	**DF**	**SF**	**DF**	**SF**	**DF**	**SF**
Sample 1	0.26	0.40	0.22	0.44	0.34	0.46	0.25	0.61	0.29	0.39	0.24	0.49
Sample 2	0.28	0.39	0.27	0.47	0.32	0.40	0.28	0.54	0.27	0.39	0.24	0.48
Sample 3	0.35	0.45	0.35	0.48	0.35	0.48	0.39	0.56	0.33	0.45	0.35	0.46

comfort, enhanced stability, promotion of a natural gait, and increased energy rebound [19]. These advantages provided the wearer with a more comfortable, stable, and efficient walking experience.

DISCUSSION

Sole material

Research shows that the shoe soles of the Terracotta Warriors from the Qin Dynasty were typical examples of multi-layered shoe soles, and they were made from ramie fabric. The earliest evidence of traditional Chinese multi-layered cloth shoes can be traced back to the kneeling statues of warriors from the Zhou Dynasty, which dates back to 1046-771BC [20]. The shoe sole imprints found on these kneeling statues closely resemble those found on the Terracotta Warriors, suggesting that the production technique of multi-layered cloth shoes was already quite mature in ancient times. According to the "Dictionary of Chinese Footwear Culture" there is evidence that during the pre-Qin period (770 – 221 BC), cloth shoes with shoe soles made of hemp, hemp cloth or silk were already being used [21]. In 1979, shoe soles made from woven hemp fabric were discovered at the Maquanwan site, which dates back to the Han Dynasty. These discoveries further confirmed the historical use of hemp fabric in shoe production in ancient China.

Sole structure design

The Terracotta Warriors were burial objects from the Qin Dynasty in ancient China, and their sole design reflected the level of shoe-making technology and craftsmanship during that time. Firstly, the shoe sole of the Terracotta Warriors was divided into different zones – the forefoot, midfoot, and heel – based on the actual needs of the human foot. This design aimed to provide optimum comfort, support and durability, thereby optimising the structure and performance of the shoe sole and improving the overall quality of the shoe. The forefoot and heel areas of shoe soles usually require good cushioning performance and wear resistance to protect the feet from impact and abrasion, hence the more densely arranged patterns in these two areas [22]. The midfoot area, located between the forefoot and heel, played a connecting and balancing role and needed to provide a certain level of support and stability [23]. Secondly, the pattern design of the shoe sole helped increase the friction between the shoe sole and the ground, thereby providing better slip resistance [24]. Lastly, the shoe sole adopted a layered structure known as "qiancengdai", with each layer made of ramie material. This material was lightweight, thin, soft, breathable, and moisture-absorbing, providing sufficient comfort and protection for the feet [25]. Overall, the design of the Terracotta Warrior's shoe sole emphasized comfort and slip resistance, reflecting the meticulous and detail-oriented approach to shoe-making in ancient China. These designs have had a significant influence on the subsequent development of shoe production.

Sole's performance

The main factors influencing the slip resistance of the sole were the contact area, contact surface, sole material, and sole pattern [26]. Slip resistance was primarily evaluated by assessing the magnitude of frictional force, with higher frictional force indicating better slip resistance. In terms of sole material and contact medium, Irvine et al. [27] found that different shoe materials showed different slip resistance performance, with significant differences between dry and wet conditions. Most shoe materials exhibited good slip resistance in dry conditions but performed poorly in wet conditions, such as EVA, TPR, rubber, and PU materials [28]. Chang et al. also indicated that compared to dry conditions, the coefficient of friction of the sole was lower in wet conditions, indicating a poorer slip resistance [29]. However, the results of this study showed that all three samples had higher coefficients of friction under humid conditions, which was contrasted with the results of previous studies. One of the major differences could be observed in the use of sole materials. Previous experiments primarily focused on non-absorbent materials such as rubber, while we used shoe soles made of textile fabric, which was absorbent. Li et al. [30] suggested that water reduced the friction between the sole and the ground, as it hindered their contact and molecular bonding. Hence, the absorbent nature of the textile fabric as a sole material would facilitate better contact between the sole and the ground, resulting in an increased coefficient of friction under wet and slippery conditions. It was important to note that using textile fabric as a sole material may have certain limitations in terms of wear resistance and durability. Therefore, when applying textile fabric in practical production and design, its absorbent properties should be considered alongside other performance indicators, and a comprehensive evaluation should be conducted.

In general, the opposite of stiffness was referred to as “flexibility” [31]. The flexibility of shoes was influenced by factors such as outsole hardness, materials, and structure. Studies showed that the stiffness of the outsole material was significantly greater than that of the upper material, making it the primary influencing factor on shoe flexibility [32]. Typically, shoes with a thinner sole had better flexibility. In this study, all three samples had a sole thickness of 1.5 cm. Therefore, the thickness of the shoe sole was not considered as a factor affecting flexibility and will not be discussed. Through comparing the three samples and considering the flexibility evaluation results of this study, the Terracotta Warrior replica shoe demonstrated superior performance in terms of flexibility, which can be attributed to its structure and craftsmanship. In terms of outsole structure, research has indicated that small and dense sole patterns were lighter and more flexible compared to large sole patterns [33]. However, all three samples had small and dense sole patterns, with differences in their distribution and proportion. The distribution and proportion of the sole pattern in the Terracotta Warrior replica shoe (Sample 1) were better aligned with the natural walking gait of humans. Generally, during normal walking, most bending activities occur in the metatarsophalangeal joint region [34]; while this region accounts for approximately one-third of the entire foot. Interestingly, the dense pattern area in the forefoot of the Terracotta Warrior’s shoes also accounted for one-third of the entire shoe sole, which conforms to ergonomics and facilitates better flexibility of the outsole. Regarding the outsole material, softer materials typically exhibit better flexibility, while rigid materials restrict the bending ability of the outsole. The Terracotta Warrior replica shoe utilized ramie material, which was lighter and thinner compared to cotton fabric, providing better flexibility. In conclusion, the Terracotta Warrior replica shoe demonstrated advantages in terms of flexibility, which was attributed to its outsole structure that aligned with the natural walking gait and the use of flexible ramie material.

CONCLUSIONS

Overall, this study first analysed and reconstructed the shoe sole and structure of the Terracotta Warrior's shoes, and then suitable materials were chosen for fabrication based on a thorough literature review; finally, by employing modern evaluation techniques for shoe structure and functionality, it was established that the shoe of the Terracotta Warrior’s shoes exhibit notable advantages in terms of flexibility and slip resistance. These advantages demonstrated shoes played a vital role in supporting the soldiers of the Qin Dynasty, contributing to their ability to enhance their combat capabilities and unify China 221 BC. These novel findings offer valuable insights into the structure and functionality of ancient shoes.

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