Body shape morphology representation and prototype pattern optimisation by polar diameter on female students' "waist-to-thigh" zone

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ABSTRACT – REZUMAT

Body shape morphology representation and prototype pattern optimisation by polar diameter on female students' "waist-to-thigh" zone

Traditional prototype patterns are typically generated using proportional formulas based on size specifications. This will only receive identical prototype patterns under the same size specification, directly leading to significant fit issues due to morphology differences. A 3D point cloud of 353 female students was scanned, and the cross-section layers of the 'waist-to-thigh' zone were determined. A polar radial was extracted to represent the surface morphological difference. Subsequently, the pattern based on the surface flattening was optimised. Additionally, the fitness was evaluated by the subjective assessment. The results showed that the polar radial could represent the body morphological difference even under the same size specification. Based on the morphological difference, the 160/68A could be divided into three categories: 160/68A-Type-I, Uniform (46.79%), 160/68A-Type-II, Flat subelliptic (37.01%) and 160/68A-Type-III, Convex subcircular (16.2%). The corresponding optimised pattern could effectively improve the garment's fitness by integrating the body morphology while maintaining original size specifications. Particularly in the waist and side seam region, the dressing pressure had been effectively solved because the pattern is more in line with the shape morphology characteristics. These findings will contribute to the fitness improvement of the same size specification.

Keywords: *body morphology, pattern generation, surface flattening, garment fitness, pattern optimisation*

Reprezentarea morfologică a formei corpului studentelor și optimizarea prototiparelor pe baza diametrului polar în zona "talie-șolduri"

Prototiparele tradiționale sunt generate, de obicei, folosind formule proporționale bazate pe specificații de mărime. Această abordare generează prototipare identice doar pentru aceeași specificație de mărime, ceea ce duce direct la probleme semnificative de potrivire din cauza diferențelor morfologice. A fost scanat un nor de puncte 3D al unui număr de 353 de studente și au fost determinate straturile secțiunii transversale din zona "talie-șolduri". S-a extras un parametru radial în coordonate polare pentru a reprezenta diferența morfologică a suprafeței. Ulterior, modelul bazat pe aplatizarea suprafeței a fost optimizat. În plus, potrivirea a fost evaluată prin evaluare subiectivă. Rezultatele au arătat că parametrul radial în coordonate polare poate reprezenta diferența morfologică a corpului chiar și în cazul aceleiași specificații de mărime. Pe baza diferenței morfologice, 160/68A a putut fi împărțit în trei categorii: 160/68A-Tipul I, Uniform (46,79%), 160/68A-Tipul II, subeliptic plat (37,01%) și 160/68A-Tipul III, subcircular convex (16,2%). Modelul optimizat corespunzător ar putea îmbunătăți în mod eficient potrivirea articolului vestimentar datorită integrării morfologiei corpului, menținând în același timp specificațiile originale de mărime. În special în zona taliei și a cusăturii laterale, presiunea exercitată de îmbrăcăminte a fost rezolvată în mod eficient, deoarece modelul este mai în concordanță cu caracteristicile morfologice ale formei corpului. Aceste constatări vor contribui la îmbunătățirea potrivirii pentru aceeași specificație de mărime.

Cuvinte-cheie: *morfologia corpului, generarea tiparelor, aplatizarea suprafeței, potrivirea articolelor vestimentare; optimizarea tiparelor*

INTRODUCTION

Statistics indicated that 67% consumers prioritise garment fitness over factors such as style, colour, and price [1]. This underscores the garment's fitness as a crucial determinant of both quality and consumer satisfaction, making it a core aspect of garment ergonomics [2, 3].

A well-fitting pattern is essential for achieving garment fitness [4]. Among various pattern-making methods, the prototype pattern method is the most widely used in industrial production due to its balance between industrialisation and personalisation. However, prototype methods, such as the Japanese Bunka, Dressmaker, and Donghua prototypes, rely on proportional formulas based on size specifications [5]. However, individuals under the same size specification may have different body morphologies [6]. Size-based prototype patterns fail to effectively capture morphological variations in contour, posture, and proportion, leading to noticeable fitness issues under the same size specification [7]. Thus, it is crucial to incorporate body morphological information into the prototype pattern generation. It will be an important means of solving these garment-fitting problems.

To optimise pattern generation based on morphological differences, researchers have explored several approaches. One method involves optimising prototype patterns by incorporating morphological parameters beyond basic body measurements, such as chest girth, waist girth, hip girth, shoulder width, etc. [8, 9]. Additionally, more detailed morphological parameters, like shoulder sloping, volume of abdomen, posture, etc., are also involved in refining the garment's fitness [10]. While these approaches improve garment fit, they also increase the complexity and slow down the pattern generation process [7]. To address this, virtual try-on technology provides an alternative by enabling real-time pattern adjustments in a digital environment [11]. This allows continuous adjustments without the physical garments. For this purpose, Sohn et al. [12] developed the virtual try-on framework to adjust the pattern to improve fitness. Ding et al. [4] designed and optimised the men's garment block pattern in CLO 3D. And the dressing pressure and actual wearing were used to reflect the garment's fitness. Meanwhile, the collaborative learning in the practice teaching of garment 3D virtual fitting to co-design and make their own garments was proposed [13, 14]. Recently, AI-integrated virtual technologies have also emerged [15]. The fitness could be further enhanced by leveraging machine learning or deep learning to analyse body shape variations and predict optimal garment adjustments. However, these applications are mainly aimed at garment design, with manual adjustments making the process time-consuming.

Another approach focuses on optimising patterns based on the human body subdivision. Lei [16] analysed the limitations of the prototype pattern, particularly in the representation of complex body shapes. Furthermore, the human body subdivision was proposed to enhance the matching degree between pattern and body morphology [17, 18]. Meanwhile, this method has been demonstrated to be effective in reducing fitness problems, especially in irregular or asymmetrical morphological [19]. Pandarum et al. [20] utilised a new normative method based on the scanning data to subdivide the human body into nine morphotype categories, acquiring the morphological features. Similarly, Gu et al. [17] combined the k-means cluster and discriminant rules to classify the human body into four categories. Subsequently, the surface flattening was used to obtain the corresponding subdivision patterns. We also proposed the space vector index to represent and quantify the body surface morphology; the corresponding patterns were also obtained [21]. However, these methods fail to capture the morphological difference under the same size specification, directly limiting improvements in garment fitness. To bridge this gap, morphological variations are first systematically analysed. Then, these variations are integrated into prototype pattern generation to enhance fitness while maintaining original size specifications.

In this study, the integration of morphological differences under the same size specification was proposed. Trousers were chosen as the experimental samples, focusing on the waist-abdomen-hip zone due to its complex morphology. Polar radials were extracted from the cross-section layers for precise morphological characterisation. PCA and K-means clustering were employed to classify target zones, followed by surface flattening to optimise corresponding patterns. Finally, virtual fitting evaluations were conducted to assess improvements. The findings enhance garment fitness by systematically incorporating morphological differences into prototype pattern generation. It not only enhances garment fitness but also provides a reference for mass customisation in the apparel industry by integrating morphological analysis techniques.

EXPERIMENT SECTION

Anthropometric

A total of 353 female university students, aged from 18 to 25 years, were recruited for this experiment, exceeding the minimum required sample size of 282 as determined by the minimum sample size based on the Chinese national standard GB/T 22187-2008. After outlier testing and descriptive analysis, 307 valid samples were determined, meeting the experimental sample requirements. Then, to obtain 3D cloud data, the $[TC]^2$ body scanner (NX-16, America) was utilised. Following ISO 20685-1:2018(E), the scanning garment should be minimal, with the subjects' acceptance, considering the cultural differences. And the mean value of three-time-repeated scanning to reduce systematic error. The experiment was conducted in a controlled environment with the temperature of (27±3) ºC and the relative humidity of (60±5)%.

Basic cross-section extraction

Based on the relationship between the lower body morphology and trousers' structure, which could be divided into four areas: fitness, activity, free and design area. The "waist-to-thigh" zone is the primary factor influencing trousers' fitness, while the zone below the thigh root is designated as the design area. Thus, the 'waist-to-thigh' zone was selected as the target zone (figure 1). Considering the correspondence between the lower body morphology and the trousers' structural lines, the waist, abdomen, hip and thigh were selected as the basic cross-sections for analysis.

The point-cloud data derived by 3D scanning was imported into reverse engineering (*Imageware 13.2*) to reconstruct the human body with unrelated parts removed. The Parallel Point Cloud Section was applied to extract the basic cross-sections, following the approach outlined in [21]. Cross-sections extracted from scanned data often contain noise and errors due to equipment limitations, tester variability, and

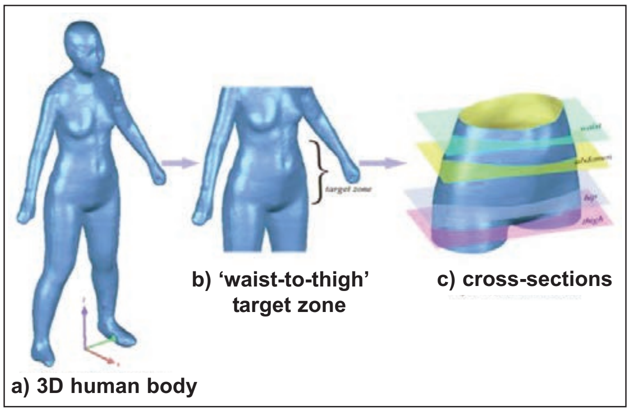


Fig. 1. Determination of basic cross-section

others. To address these, mending, smoothing, and straightening processes were applied to obtain continuous and smooth point-cloud data using MATLAB 2017a (Math Works, Inc.) The producers were referred to Zhang’s study [22].

Polar radial extraction

Curve fitting

To generate cross-section curves that align with morphological characteristics, the processed point-cloud data required further curve fitting. Considering the sparse distribution, high iteration, and nonlinear nature of the cloud data, the cerebellar model articulation controller (CMAC) neural network was employed to fit the cloud data into the cross-section curve. Unlike conventional neural networks, the CMAC is a local approximation model that eliminates the need for predefined network depth and neuron numbers. These features endow the CMAC with significant advantages in convergence speed, local generalisation capability, and fitting accuracy. Taking the waist cross-section as an example, the fitting results were illustrated in figure 2, *a* and *b*. It demonstrates that the model achieves the desired fitting accuracy through parameter tuning.

Polar radial extraction

Based on the sampling points along the cross-sectional curve, an orthogonal coordinate system was constructed. This system utilises radial lengths at various positions to characterise the morphological variations. The X-axis aligns with the sagittal plane and the Y-axis with the coronal plane. And the intersection was the centre point. Sampling points were marked every 10º along the cross-section curve, and the horizontal vector was used to define the polar length. Then, a total of 37 feature points were extracted. Figure 2, *c* illustrates the distribution of these 37 points and the polar radial. The corresponding polar radial lengths at different positions were illustrated in figure 2, *d*. To clearly illustrate the radial differences at different positions, the extracted sampling points were divided into four regions: Back-Middle (*No.*$_{i1}$ to *No.*$_{i7}$ and *No.*$_{i31}$ to *No.*$_{i1}$, purple), Left-Side (*No.*$_{i1}$ to *No.*$_{i7}$ and *No.*$_{i31}$ to *No.*$_{i1}$, green), Right-Side (*No.*$_{i1}$ to *No.*$_{i7}$ and *No.*$_{i31}$ to *No.*$_{i1}$, pink) and Front-middle (*No.*$_{i13}$ to *No.*$_{i25}$, yellow).

RESULTS AND DISCUSSION

Determination of the target size specification

The process of determining the target size specification was mainly divided into three steps.

(1) Height selection: The 160 category is the highest proportion under the national standard (GB/T 1335.2-2008), accounting for 37.79%.

(2) Specification within height group: By combining the height category with type A, the 160-A was formed.

(3) Circumference selection: Within the 160-A framework, the 160/68 A size specification has the highest proportion, reaching 43.06%. Then, the final target size specification (160/68 A) was determined. It also aligns with the distribution phenomenon defined by the national standard. Additionally, normality testing was conducted to reveal that both height and size type generally followed the normal distribution. Based on the distribution results, the 31 corresponding samples under the 160/68 A occupied the largest proportion. Thus, these 31 samples were selected as the target size specification.

Human body subdivision (160/68 A)

PCA and K-means cluster analysis

After determining the target size specification, the polar radial reached 4588-dimensional (31×4×37), directly affect the algorithm accuracy and speed. To address this, Principal Component Analysis (PCA) was employed to reduce dimensionality while retaining essential information. Through the PCA of the

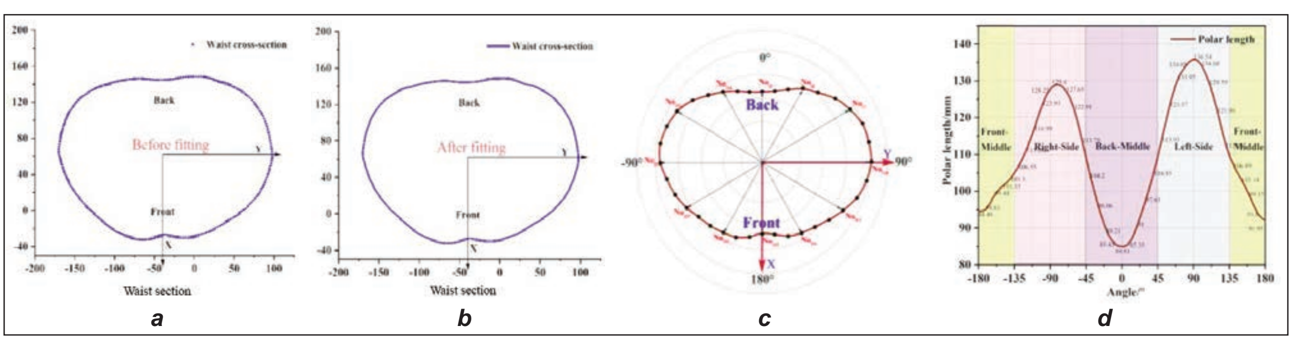


Fig. 2. Polar radial extraction: *a* – before fitting; *b* – after fitting; *c* – points distribution; *d* – polar lengths

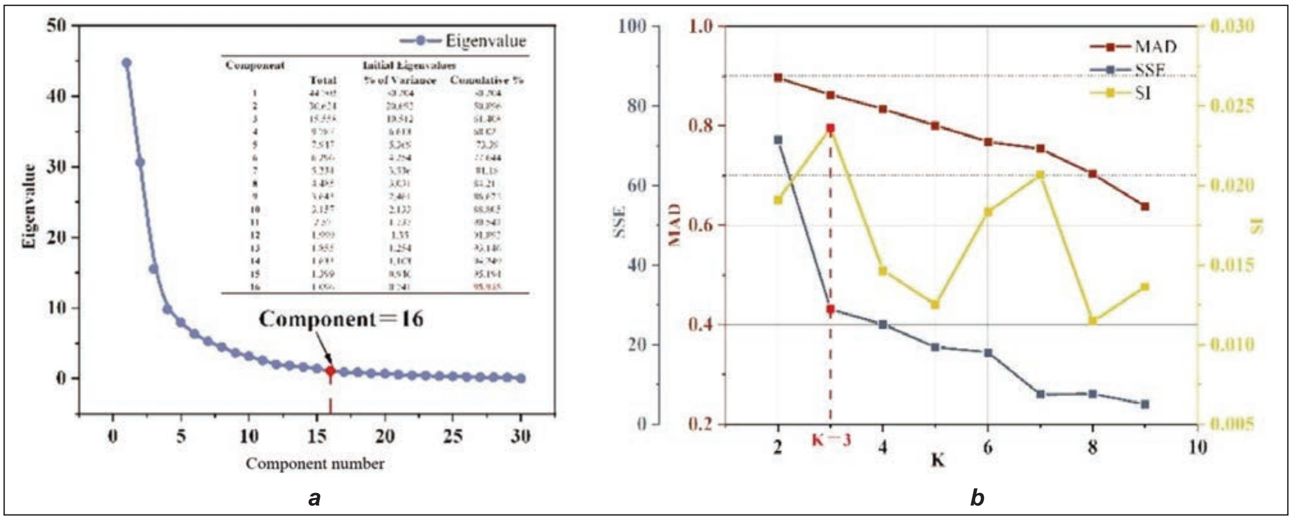


Fig. 3. PCA and K-means cluster analysis: *a* – PCA analysis; *b* – evaluation of cluster number *k*

‘princomp’ function in Matlab, PCA yielded a cumulative contribution rate of ρ = 95.762% was obtained (figure 3, *a*). It indicated that 16 principal components could sufficiently describe the morphological characteristics of the target zone.

Next, the K-means was applied for human shape subdivision. However, the choice of cluster number *k* significantly affects the algorithm’s performance. To determine the optimal *k*, three evaluation metrics were employed: mean absolute deviation (MAD), the sum of squares due to error (SSE) and silhouette index (SI). As shown in figure 3, *b*, the MAD showed a downward trend with minimal slope variation, indicating no abrupt changes. The SSE decreased sharply at 3, forming an elbow point, suggesting that *k* = 3 is the optimal cluster number. Simultaneously, the SI reached its peak at *k* = 3, also supporting this choice. Thus, the final *k* was determined to be 3.

Human body subdivision

After determining the number of clusters as 3, the human body subdivision was realised using K-means. The 160/68A was further subdivided into three categories: Type-I (46.79%) > Type-II (37.01%) > Type-III (16.2%). And the three subdivision results of the intermediate shape are shown in figure 4. It could be seen that the morphological differences among them were evident. This finding highlights that individuals with the same size data can exhibit distinct body shapes, which is a key factor contributing to garment unfitness.

The morphological differences were illustrated: Type-I (Uniform): the overall shape is moderately cocked, with a balanced contour and an appropriate waist-to-hip thickness. Type-II (Flat subelliptic): the overall body shape is relatively flat, with a wider waist, abdomen, and hip, but smaller waist-to-hip thickness. Type-III (Convex subcircular): the overall shape is rounded, with a prominent waist, abdomen and hip, resulting in a larger waist-to-hip thickness.

Shape morphology representation

To highlight the morphological differences among the 3 subdivision types, figure 5, *a* illustrated the overlapped results of the same cross-sections, while figure 5, *b* shows the difference in the polar radial. Among them, Type-I was used as the reference. As we can see, in the waist cross-section, Type-II exhibits a larger polar length than Type-I on the right and left sides, but a smaller one in the front and back-middle. In contrast, Type-III demonstrates the opposite phenomenon relative to Type-II. A similar trend is observed in the abdomen. Although the differences are more pronounced, with a maximum deviation of 1.84 cm. In the hip, Type-II shows a larger polar length, primarily on the right side, and a smaller one in the front-middle. Conversely, Type-III exhibits larger values than Type-I in the front and back-middle areas, while being smaller in the lateral middle, with a maximum difference of 0.90 cm. In the thigh root, the morphological differences show a similar phenomenon between Type-II and Type-III. They are all larger than Type-I in the front and back-middle positions, but smaller in the lateral middle regions. Overall, the shape morphology of Type-II is relatively flat, while that of Type-III is a convex subcircular.

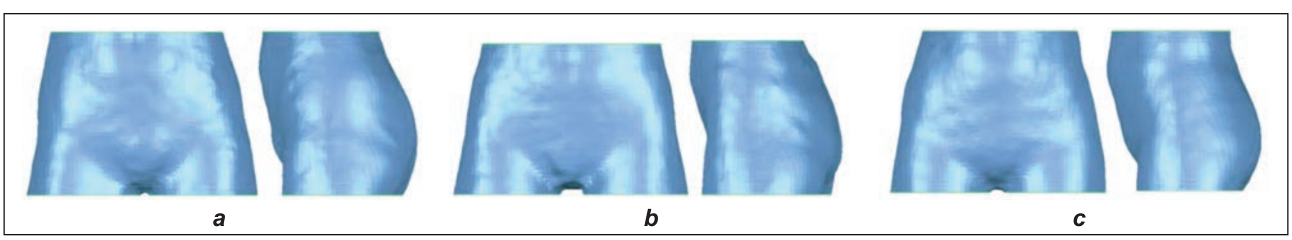


Fig. 4. Human body subdivision: *a* – 160/68A-Type-I; *b* – 160/68A-Type-II; *c* – 160/68A-Type-III

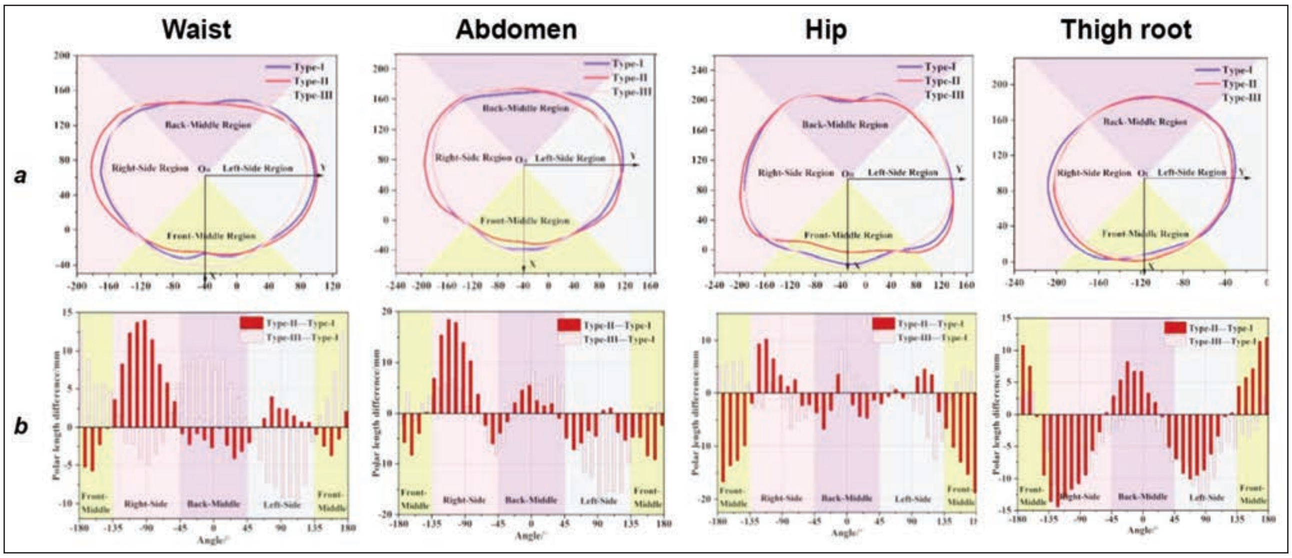
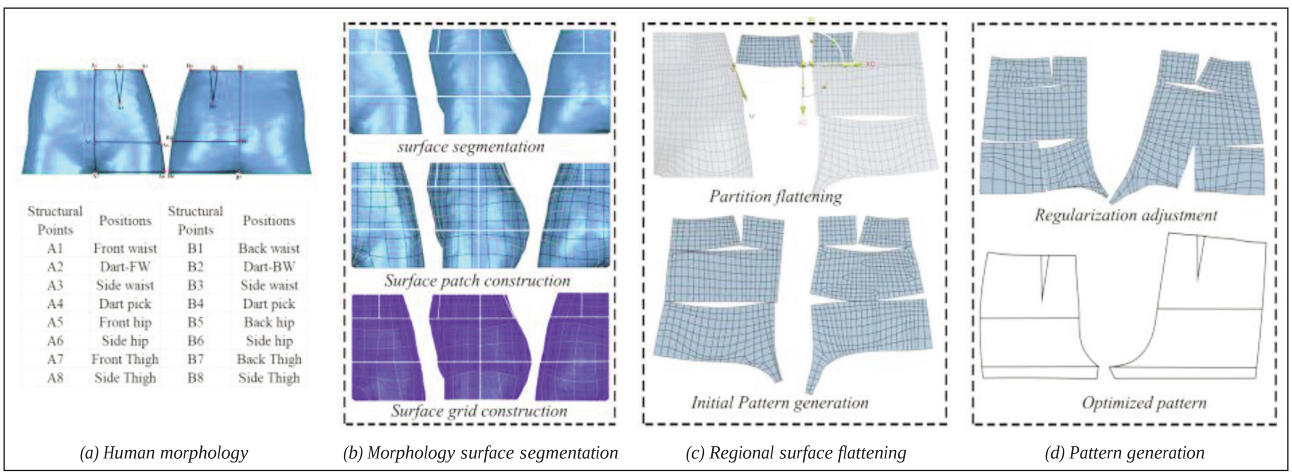


Fig. 5. Shape morphology representation and comparison



Structural Points	Positions	Structural Points	Positions
A1	Front waist	B1	Back waist
A2	Dart-FW	B2	Dart-BW
A3	Side waist	B3	Side waist
A4	Dart pick	B4	Dart pick
A5	Front hip	B5	Back hip
A6	Side hip	B6	Side hip
A7	Front Thigh	B7	Back Thigh
A8	Side Thigh	B8	Side Thigh

Fig. 6. Optimised pattern based on surface flattening

Prototype pattern optimization

Pattern optimisation based on surface flattening

To obtain the pattern incorporating morphological characteristics, the surface flattening method was applied. This approach not only enables the transformation of 3D surface geometry into 2D planar patterns but also allows the integration of local curvature and deformation constraints, ensuring that the resulting flat patterns maintain fidelity to the original 3D form. According to the structure characteristic of the trousers' prototype pattern, the 16 structure points corresponding to the target zone were selected. Then these points were divided into several regions (figure 6, *a*). Then, the morphological surface was segmented by constructing patches and grids on the 3D body surface model, generating the fitted surface (figure 6, *b*). For each segment part of the morphological surface, surface flattening was performed on the fitted surface to generate an initial pattern (figure 6, *c*). Since the surface morphology is 3D, the initial flattened surface pattern has a certain degree of inclination and curvature. The regularisation adjustments were applied to the structural lines based on the prototype patternmaking rules. As a result, the optimised pattern was acquired in figure 6, *d*.

Figure 7 illustrates the three subdivision patterns and pattern prototypes under the 160/68A size specification. As we can see, although the obvious waist circumference and length are the same, the local details show differences. Compared with the pattern prototype, different subdivision types, dart sizes, and locations of the front/back pattern pieces are also

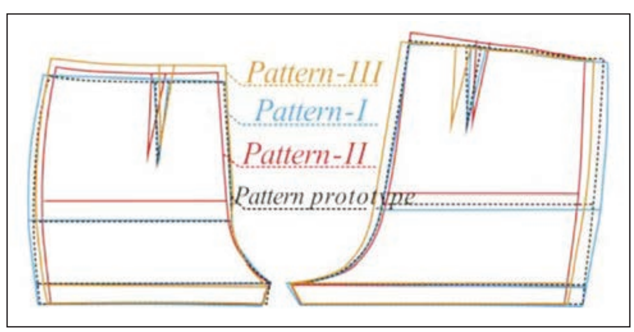


Fig. 7. Comparison of different subdivision patterns

Table 1

DETAILED DATA OF THE HUMAN BODY					
Height (cm)	**Weight (kg)**	**Waist circumference (cm)**	**Hip circumference (cm)**	**Thigh circumference (cm)**	**Subdivision category**
161.4	48	67.6	87.4	52.5	Type-II

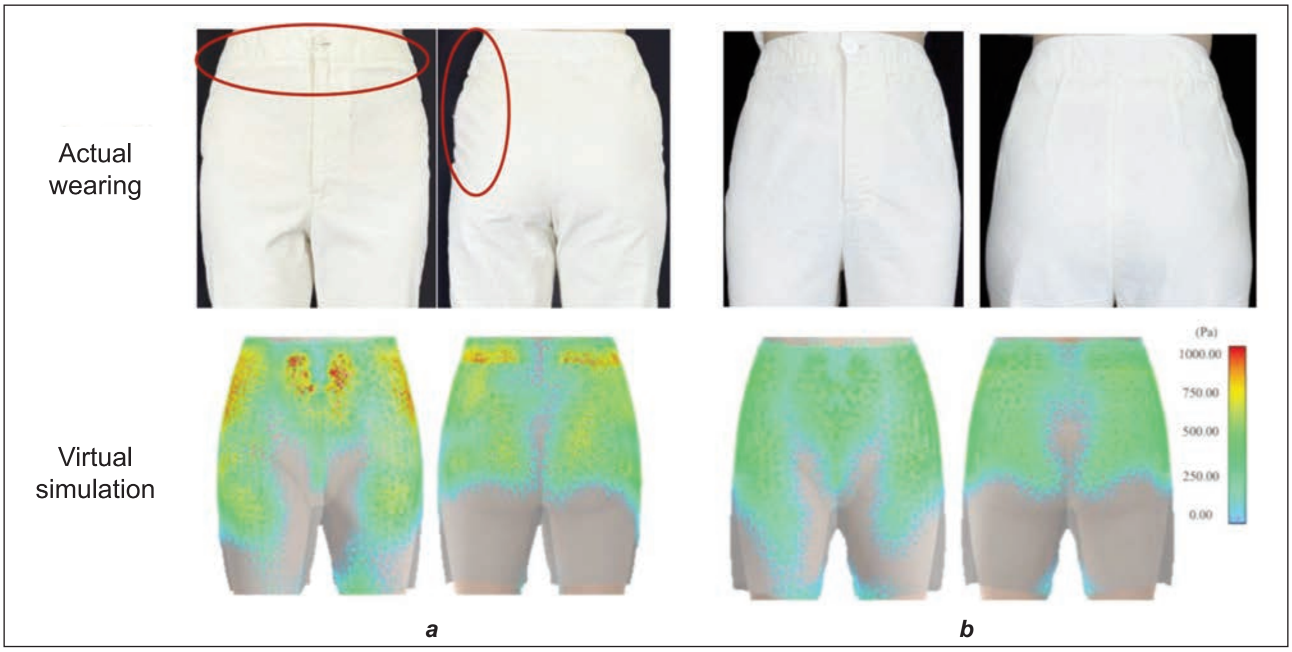


Fig. 8. Results of fitness comparison: *a* – pattern prototype; *b* – pattern-II Flat subelliptic

different. Among them, the waist width becomes Pattern-III> Pattern-I> Pattern-II, the same as the back waist dart location. Furthermore, the difference between the waist-abdomen is Pattern-I> Pattern-II> Pattern-III. This also basically conforms to the morphological representation illustrated in the previous section.

Fitness comparison

To demonstrate the fitness improvement of the proposed method, both actual wear trials and virtual simulations were conducted. Among them, the target subject was recruited, and the detailed data are presented in tabel 1. According to the subdivision results, the subject belongs to the Type-II category. Then, the materials used in actual were the 2222 plain fabric. And the actual garment was made by the tailor patternmakers based on the pattern prototype and subdivision pattern. For the virtual simulation, the detailed data of the target subject was imported into the Style 3D to generate the virtual model. The pattern prototype and subdivision pattern were then virtually sewn to make a comparison. The built-in strain map module was utilised to visualise. Figure 8 illustrates the results of the fitness comparison. As we can see, there is almost the same in the silhouette of the trousers. However, the prototype pattern produced more pronounced wrinkling and drag around the waist and side seams, indicated by yellow and red regions in the simulation. In contrast, the subdivision pattern-II conformed more closely to the body morphology characteristics, indicating blue and green in virtual simulation. These results will contribute to the fitness improvement of the trousers.

CONCLUSION

In this study, the integration of morphological differences under the same size specification was proposed to enhance pattern prototype fitness. The main conclusions were drawn as follows:

(1) Experiments showed that the polar radial could represent the body morphological difference under the same size specification. Based on the morphological difference, the "waist-abdomen-hip" zone was classified into three categories: Type-I (41.79%) > Type-II (28.79%) > Type-III (16.1%).

(2) The optimised prototype pattern could effectively improve the fitness while maintaining the original size specifications. Particularly in the waist and side seam region, the dressing pressure had been effectively solved because the pattern is more in line with the shape morphology characteristics.

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