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Multi-pose dress simulation of fully-fashioned knitted skirt based on loop structure

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Abstract

To realize the three-dimensional structure simulation and dress simulation of the fully-fashioned knitted skirt, based on the study of the structural characteristics of the fully-fashioned knitted skirt, the mathematical model of the knitted skirt pattern, the loop geometry mathematical model and the loop mesh model were established by the method of mathematical modelling. The spatial transformation relationship of each pair of triangles in the plate model and the three-dimensional surface model was calculated by using the spatial matrix. To draw a loop on the surface model's triangular patch, spatial transformation was used to calculate the grid point positions and obtain three-dimensional coordinates of the loop-type value points. Based on C# programming language, the human body model in the database was matched with the knitted skirt surface model, and the three-dimensional graphics library Open-GL and loop drawing method were used to realize the simulation of the knitted skirt dress based on the loop structure. The simulation method was tested by the dressing effects of hip skirts and umbrella skirts with different postures. The results showed that the spatial transformation could realize the fast transformation and calculate the coordinates of the loop-type value points. The C# programming language and Open-GL technologies realized the visual simulation of the fully-fashioned knitted skirt and the multi-pose dressing simulation based on the loop structure.

Keywords: Loop structure, Knitted skirt, Mathematical model, Space transformation, Multi-pose, Simulation

Introduction

With the continuous development and innovation of Internet technology, computer-aided design (CAD) has become widely used in fashion design. Conducting computer simulations of fabrics is important for research on clothing CAD and computer graphics (Li & Cohen, 2021; Shi et al., 2021). Virtual clothing display technology based on fabric structure simulations can be used to realistically reproduce clothing through virtual simulation technology and has excellent potential application value in textiles, animation, e-commerce, and other areas (Bao et al., 2021; Wang et al., 2019).

Fully-fashioned knitted skirts are increasingly favoured by consumers because they bring more comfort to consumers because of their one-piece forming (Lai et al., 2023; Zhan et al., 2021). As one of the most common women's wear styles, the fully-fashioned knitted skirt has always been loved by the majority of female consumers (Lu et al., 2022; Peng et al., 2018). In recent years, the three-dimensional simulation of knitted products has developed rapidly. Many scholars have performed extensive research on the organization and modelling of knitted garments, and proposed various models and calculation methods for the virtual simulation of knitted garments. At present, the research and calculation of knitted garment simulation can be divided into two categories. One approach involves simulating knitted garments from a microscopic point of view, and the other approach involves simulating knitted garments from a macroscopic point of view using the texture mapping method. Many scholars simulated knitted garments from the microscopic point of view of the loop structure. Several researchers (He, 2017; Sha et al., 2015) used a quadrilateral knitted mesh as the primary cycle structure, and employed an improved particle system with a three-layer structure suitable for knitted fabric simulation to display the three-dimensional display of knitted garments based on the structure of plain. Several scholars (Wu et al., 2019a, 2019b, 2021) meshed the knitting units and calculated the collision relationship between them by relaxing the loop relationship between the spring and the smoothing unit, thus realizing the knitted sweater simulation. Although the research could better simulate the physical deformation of the fabric and the loop, the proposed meshing method did not consider the knittability of the fabric, the amount of calculation was large, and the simulation results could not respond quickly.

Many scholars use the method of texture mapping to simulate knitted clothing. According to the fabrication process of sweaters, Luo et al. (2021) meshed the two-dimensional clothing pieces mapped the elements of the knitting loop according to the grid to form a two-dimensional clothing piece with knitted texture, and then realized the three-dimensional display of the sweater according to the mapping relationship between the two-dimensional clothing piece and the three-dimensional clothing piece. Igarashi et al. (2008) used quadrilaterals and triangles to represent the weft-knitted organizational structure and mapped the graphic elements of the organizational structure represented by quadrilaterals and triangles to the grid to obtain the simulation effect of the three-dimensional model. Other scholars (Wu et al., 2019a, 2019b) processed yarn images and mapped them to a loop model. This loop was hidden to determine the effect of the moire yarn or the mixed-colour yarn on the appearance of the fabric. The above texture mapping method only simply considered the fabric structure. Moreover using primitives for mapping could not truly reflect the relationship between the fabric structure.

The existing commercial knitting sweater design software also had a certain three-dimensional simulation function, but its focus was on the design of sweater structure patterns. The three-dimensional simulation model presented by the reality was limited, and it had to go through a complex and long design process.

To solve the shortcomings of the texture mapping method and the existing knitting design software could not be used to conduct three-dimensional simulations of multi-pose knitted skirts, a multi-pose simulation method based on a loop structure was proposed in this paper. The mathematical model of the knitted skirt template and the mathematical model of the loop were established. The C# programming language and Open-GL technology were used to read the human body data of different postures, the sample data of the skirt and the loop model data, and the surface model loop drawing of the knitted skirt was completed through the spatial conversion relationship so as to realize the multi-pose dress simulation of the skirt based on the loop structure.

Literature Review

Fully-fashioned knitted garments

Since the introduction of computerized flat knitting machines in the 1970s, manufacturers envisioned the production of fully fashioned knitted garments. This technology, implemented through four-needle bed computerized flat knitting machines, enables three-dimensional knitting, allowing the garment to be worn directly off the machine. This eliminates the laborious and costly necking process, fundamentally transforming the production approach for knitted products.

Underwood (2009) pioneered the use of full-fashioned technology to explore the knitting of three-dimensional preforms, incorporating structures such as spheres, cones, and tubes. Lee et al. (2013) systematically summarized the characteristics of the knitting process for fully fashioned garments utilizing data from computerized flat knitting machines and knitted products. Choi et al. (2015) delved into knitting methods employing needle-copying processes, conducting detailed tests on the strength and elongation properties of these processes. Sewell (2019) developed a prototype for full-fashioned training clothing, addressing common knitting process challenges through flow chart analysis and time assessments, suggesting applications in diverse clothing fields.

By examining the distinction between fully fashioned suits and ordinary sweaters, Liu and Cong (2020) focused on the body and collar, analyzing process design methods and forming principles to achieve the one-time formation and weaving of leisure suits. Wang et al. (2022) established a comprehensive knitted skirt template library incorporating profile compression patterns, design elements, and various moulding methods. Wang et al. (2020) conducted an in-depth exploration of the integrated forming process for fully fashioned knitted half skirts, selecting three typical styles for analysis. These studies provided theoretical insights into the style development and process design of fully fashioned knitted products, with upcoming simulation designs focusing on the full-forming skirt process.

Knitted clothing simulation

The evolution of computer graphics drove the transition of CAD display effects from a two-dimensional plane to a three-dimensional realm. Accurate three-dimensional simulation became crucial in providing users with a more realistic experience, particularly with regards to knitted clothing, a focal point of research in clothing CAD and computer graphics.

Current research on knitted garment simulation was categorized into two approaches: macroscopic simulation focusing on garment pieces using texture mapping and microscopic simulation centering on loop structures. The texture mapping method involved mapping a two-dimensional texture image to an existing fabric model, primarily simulating the two-dimensional texture. Dong (2015) demonstrated this by meshing two-dimensional clothing pieces, using texture mapping to fit them onto a three-dimensional model. However, in this method, the intricate knitting loop structure was overlooked.

An alternative microscopic perspective involved simulating knitted garments by considering the loop structure. Researchers, such as Igarashi et al. (2008), leveraged geometric methods to mesh the model surface, establishing threading geometric models between loops. This enabled the calculation of internal forces within loop connections, with yarn relaxation through physical methods achieving the final three-dimensional simulation of knitted fabric. Intriguingly, Casafranca et al. (2020) proposed a hybrid method that combines triangle and yarn models for clothing simulation. The triangle model reduced computational costs, while yarn-based models produce realistic wrinkle effects and were particularly suitable for slim and tight clothing simulations. However, its applicability to loose clothing was challenging.

Yuksel et al. (2012) introduced a unique approach by drawing loop structures in a deformed grid, simulating the physical deformation of loops. While realistic, this method was time intensive. In 2019, they achieved the conversion of knitted meshes into braided structures, demonstrating versatility. Their 2022 simulation system generated both wearable and machine-woven fabrics, processing knittability and wearability independently.

Despite these advancements, current methods were limited by their ability to smooth surfaces and struggled to accurately simulate knitted garments with wrinkle effects. Commercial flat knitting CAD software, including STOLL's M1PLUS, Fuzhou Qili Software, and SHIMA's SDS-ONE APEX3, predominantly offered two-dimensional representations of loop structure and fabric simulation. Notably, the SDS-ONE APEX3 of SHIMA allowed knitted garment try-on simulations, albeit with limitations in loop structure representation. SHIMA's SDS-ONE APEX3 could simulate the try-on of knitted garments, but it could not simulate knitted half-skirts and freely designed knitted garment styles.

In conclusion, the field of three-dimensional simulation for fully formed knitted garments held immense potential for development. Future efforts should aim at overcoming current limitations to achieve more accurate and realistic simulations, especially in fully fashioned knitted garments designed with different knitting structures.

Methods

Structural characteristics of fully-fashioned knitted skirt

Fully-fashioned knitted garments were made of loop sets, which could not be cut at random like woven garments. Different shapes could be achieved by the forming process. The basic forming process includes five categories: straight, narrowing, widening, binding-off and local knitting. The simulation objects were fully-fashioned knitted hip skirts and umbrella skirts. In the forming process, the shape of the clothing was mainly formed by narrowing. The structures used were plain and rib. The loop units involved include stitch-forming and transfer stitch units.

The fully-fashioned knitted skirt was knitted in a tubular manner. The knitting sequence on the machine ran from bottom to top, and the reduction in size was completed by the narrowing process. The needles could be divided into bright narrowing, dark narrowing, folding stitches, and flat narrowing, and the range of stitches was generally 1–3 needles (Li & Wu, 2019; Wang & Wu, 2019a, 2019b). Among these methods, the bright and dark narrowing were often used to reduce the stitches on both sides of the tubular fabric. The number of bright narrowing stitches was greater than the number of transfer stitches, thus forming a stitch flower; leading to the formation of stitch flowers. The number of dark narrowing stitches was equal to the number of transfer stitches, and the surface of the fabric was smooth and beautiful. To make the contour line of the knitted skirt smooth, the dark narrowing on the side of the knitted skirt was simulated.

Mathematical model establishment of fully-fashioned knitted skirt

Two-dimensional model mathematical model of knitted skirt

To simulate a knitted skirt, the size of the two-dimensional template according to the clothing modelling information needs to first be obtained. Therefore, it was required to model the two-dimensional template mathematically. After reading the two-dimensional template file in DXF format and obtaining the shape of the template, it was necessary to store the key point data. A set of key point data could not only be used to determine the shape and size of a specific template but also to help transform an ordinary two-dimensional template to transform into a knitted template according to the course density and wale density. Therefore, it was essential to construct a mathematical model of key points. The mathematical model of the key points of the template is a one-dimensional matrix, as shown in (1).

$$L = \left[\, l_0 \;\, l_1 \;\, \ldots \;\, l_i \;\, \ldots \;\, l_n \,\right] \tag{1}$$

In the formula: $\boldsymbol{L}$ is a one-dimensional matrix of key points; "n + 1" represents the number of key points, and l_i represents the key point of the i. When the style is different, the model's key points are also different.

The hip skirt template in the knitted skirt is shown in Fig. 1. The front pattern of the hip skirt is composed of three parts of A-front waist piece, B-front body piece and C-front hem piece and eight key points. The back pattern is composed of three parts of D-back waist piece, E-back body piece and F-back hem piece and eight key points. From the figure, it can be seen that there are two sets of key points in the hip skirt pattern. The one-dimensional arrays of the key points of the front piece and the back piece hem are shown in Formulas (2) and (3), respectively.

$$L_{Front.piece} = \left[\, l_0 \;\, l_1 \;\, l_2 \;\, l_3 \;\, l_4 \;\, l_5 \;\, l_6 \;\, l_7 \,\right] \tag{2}$$

$$L_{Back.piece} = \left[\, l_{10} \;\, l_{11} \;\, l_{12} \;\, l_{13} \;\, l_{14} \;\, l_{15} \;\, l_{16} \;\, l_{17} \,\right] \tag{3}$$

According to the key point information of the two-dimensional model, the specifications and style information of the skirt were obtained. Through the coordinates of the key points, the size data of each part were calculated, and then by setting the course density and wale density, the size data of each part were transformed into the number of knitting rows and different structures, that is, the loop data. Since each garment pattern

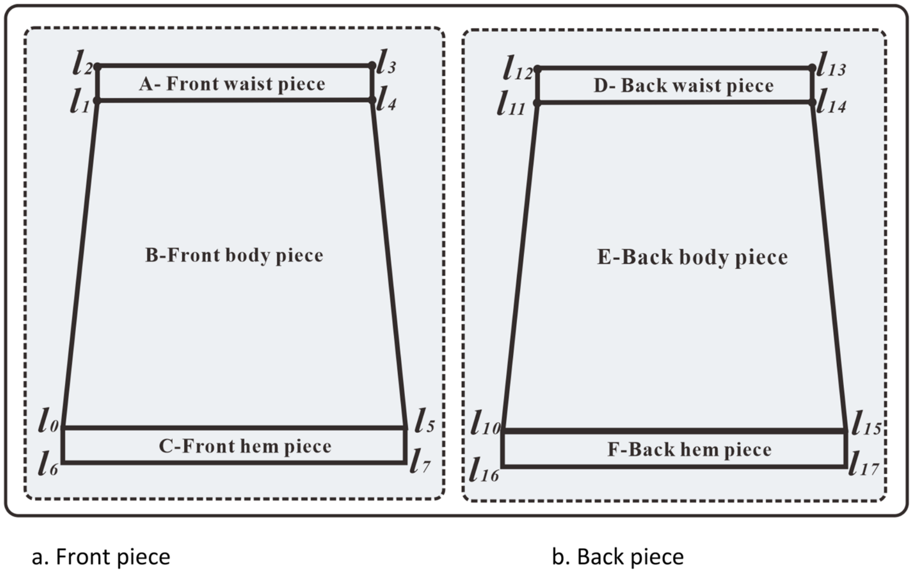


Fig. 1 Pattern of the hip skirt: **a** front piece; **b** back piece

contains multi-row and multi-column information, the mathematical model of the garment pattern is a two-dimensional matrix in the following form:

$$F = \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1h} \\ f_{21} & f_{22} & \cdots & f_{2h} \\ \vdots & \vdots & f_{ij} & \vdots \\ f_{w1} & f_{w2} & \cdots & f_{wh} \end{bmatrix} \tag{4}$$

In the formula: $\boldsymbol{F}$ is the two-dimensional matrix of the garment pattern; w is the total number of rows of the two-dimensional template; h is the number of needles at the widest position of the two-dimensional template, and f_{ij} is the loop located at the i-th course and the j-th wale. Since the outline of the garment pattern is an irregular geometric body, when $f_{ij} \neq 0$, it is represented in the outline. When $f_{ij} = 0$, it is represented outside the contour.

Establishment of the mathematical model of the loop

The geometric model of the loop

The plain stitch was formed by the yarn hooked by the knitting needle and was connected in series in the wale direction. In the actual fabric, the size and shape of the loop were not the same due to differences in the course, wale density and yarn material (Berenguer et al., 2020). In addition, the yarn diameter was not uniform due to the friction and tension, bending or other forces generated by the mutual sleeve between the loops. The main purpose of this paper was to simulate the three-dimensional structure simulation and multi-pose dressing simulation of full-fashioned skirts. To establish a loop geometric model and reduce the number of calculations, idealized assumptions regarding uniform yarns, smooth and continuous twist-less yarns, and symmetrical loop structures were made in this paper according to the central axis (Li et al., 2019). The loop was composed of needle loop, sinker loop and leg. With reference to the classic

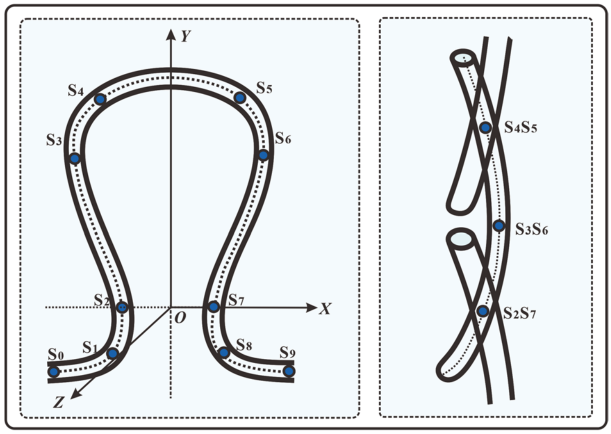


Fig. 2 Geometric model of plain stitch loop: **a** front view; **b** side view

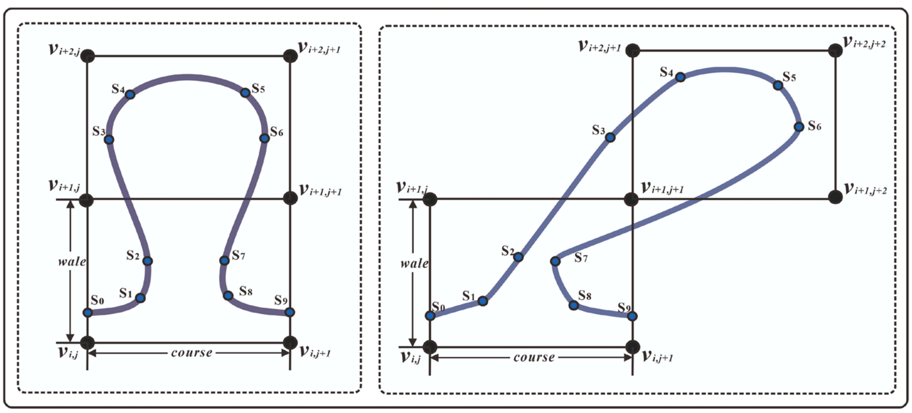


Fig. 3 Grid-based model: **a** grid-based model of plain stitch loop; **b** grid-based model of transfer stitch loop

two-dimensional Peirce loop model (Peirce, 1947), control points (type points) were added to the three sections of the loop to establish a 10-point model of the flat-knitted loop, as shown in Fig. 2. The O-point was the center point of the loop, and the three points of S_2, O and S_7 were assumed to be on the X axis.

Mesh model of loop

Since the change in the loop in the Z direction was negligible when the loop was deformed, the Z direction was ignored when the grid model was established. The grid model of the plain stitch is shown in Fig. 3a. The loop grid model was established with the loop height wale and the loop distance course as the length and width of the grid, respectively. The actual loop height and loop distance were calculated according to the horizontal and vertical density of the actual fabric. Taking the lower left corner particle as the starting point, the six vertices in the rectangle were the six particles of the grid, which were represented as $V_{i,j}$, $V_{i,j+1}$, $V_{i+1,j}$, $V_{i+1,j+1}$, $V_{i+2,j}$ and $V_{i+2,j+1}$ (where i represents the number of horizontal columns of the particle in the model and j represents the number of particles in the vertical line of the model).

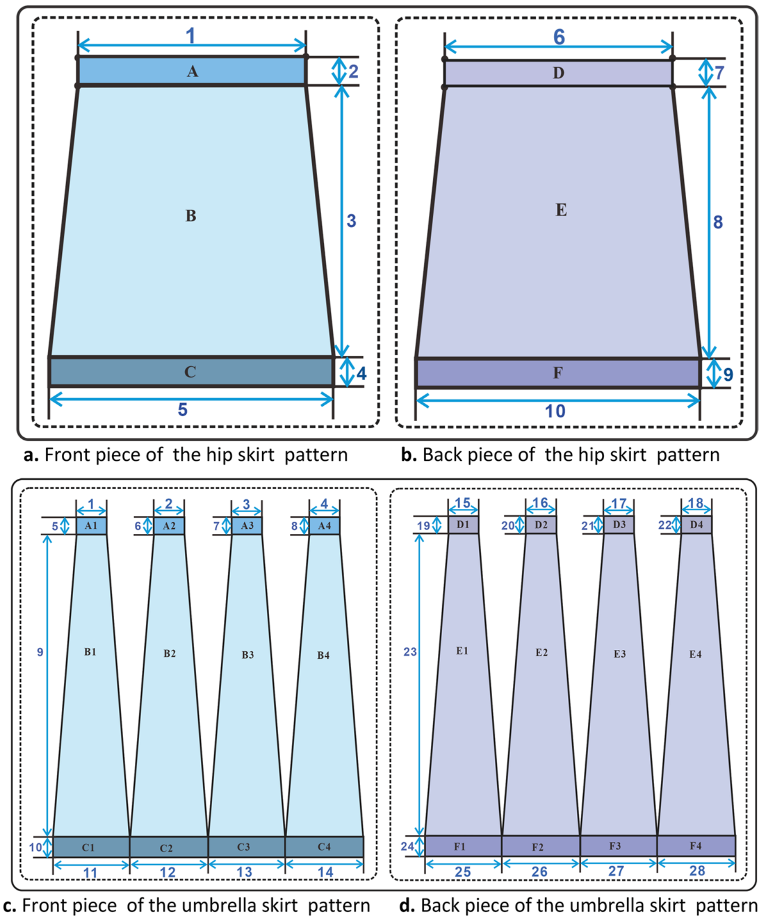


Fig. 4 Patterns of the hip skirt and the umbrella skirt: **a** front piece of the hip skirt pattern; **b** back piece of the hip skirt pattern; **c** front piece of the umbrella skirt pattern; **d** back piece of the umbrella skirt pattern

To make the outline of the knitted skirt smooth and aesthetically pleasing, the equidistant segmentation method was usually used to divide the parts that need to be reduced or add the needle. After the segmentation was completed, the needle was reduced or added at the equidistant point (Li et al., 2019).

Narrowing and widening were completed by the transfer of loops. The loops were transferred to other knitting needles during the knitting process. It was widely used in the forming and pattern of knitted garments. The transfer of loops can also led to the formation of other structures, such as mesh structures and cable structures (Lu et al., 2020; Qiu & Wu, 2019). The value points of the transfer loop were changed from the plain structure, where S_4, S_5 and S_6 move to the right according to the number of needles of the transfer needle, and the coordinates of S_2 and S_3 in the XOY plane were obtained by staggered transformation in the X direction. As shown in Fig. 3b, it was a transfer mesh model used to shift one needle to the right.

Table 1 Specific measurements for hip skirt pattern and umbrella skirt pattern

Skirt Name	Number	Part	Measurement value(Unit: cm)
Hip skirt pattern	1	Front waist width	32
	2	Front waistband width	4
	3	Front skirt length	38
	4	Front hem length	4
	5	Front hem width	40
	6	Back waist width	32
	7	Back waistband width	4
	8	Back skirt length	38
	9	Back hem length	4
	10	Back hem width	40
Umbrella skirt pattern	1/2/3/4	Front waist width/4	8
	5/6/7/8	Front waistband width	4
	9	Front skirt length	76
	10	Front hem length	5
	11/12/13/14	Front hem width/4	20
	15/16/17/18	Back waist width /4	8
	19/20/21/22	Back Waistband width	4
	23	Back skirt length	76
	24	Back hem length	5
	25/26/27/28	Back hem width/4	20

Fig. 5 Actual images: **a** hip skirt; **b** umbrella skirt

Multi-pose dress simulation of fully-fashioned knitted skirt

Human modelling and size

The human body model is the basis of dress simulation, so it is necessary to establish a suitable three-dimensional human body model. This dress simulation experiment is based on the standard human body of 160/84 A type in GB/T 1335.2-2008 'women's clothing size' for three-dimensional human body modelling.

A three-dimensional human body model was scanned using a three-dimensional human body scanner, or created using modeling software such as Maya, 3Dmax, ZBrush, or through human body modeling based on deep learning (Huang et al., 2019; Zheng et al., 2021). In this experiment, the required human body was established from modelling software. The three-dimensional human body was generated in OBJ format and then the dressing simulation was carried out. The human Pose1 posture was selected as the initial posture for dress simulation. The Pose1 is a common human A-pose model. The specific measurements of the pose 1 human model are as follows: front chest circumference is 43 cm; back chest circumference is 41 cm; front waist circumference is 32 cm; back waist circumference is 34 cm; front abdominal circumference is 40 cm; back abdominal circumference is 38 cm; front hip circumference is 42 cm; back hip circumference is 48 cm.

Pattern size and structure

In this experiment, hip skirts and umbrella skirts, which were common in knitted skirts, were selected for the experiments. The front and back patterns of the hip skirt are shown in Fig. 4a and b, wherein Part A is the front waist piece, and the structure is 2×2 rib structure; Part B is the front body piece, which is a plain structure; Part C is the front hem piece, which is a 2×2 rib structure. Part D is the back waist piece, which is a 2×2 rib structure; Part E is the back body piece, which is a plain structure;

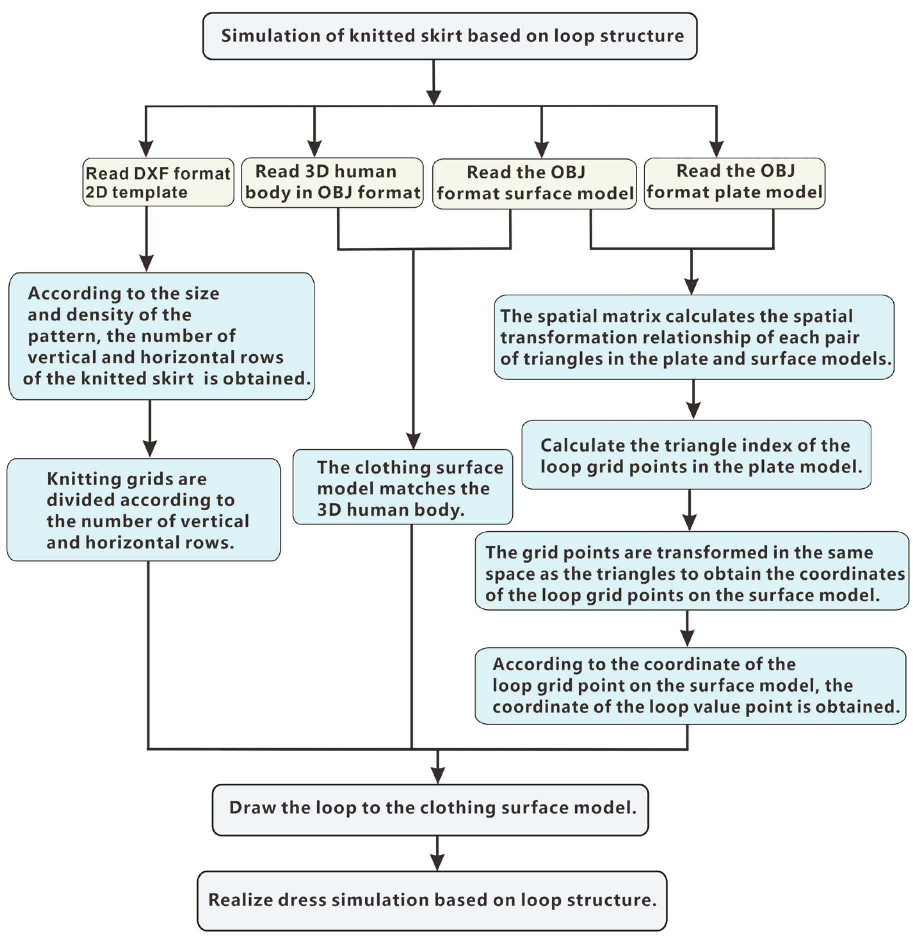


Fig. 6 Research roadmap

Part F is the back hem piece, which is a 2 × 2 rib structure. The front and back patterns of the umbrella skirt are shown in Fig. 4c and d, wherein the A1, A2, A3, and A4 parts are the front waist pieces, the sizes of the four pieces are equal, and they are 2 × 2 rib structures; B1, B2, B3 and B4 parts are the front body pieces, and the four parts are equal in size, which together form the front body piece, and they are plain structures; C1, C2, C3, and C4 parts are the front hem segments; the four parts are equal in size, and they are 2 × 2 rib structure. The D1, D2, D3 and D4 parts are the back waist segments, the four parts are equal in size, and they are 2 × 2 rib structure; the parts of E1, E2, E3 and E4 are the back body pieces, the four parts are of the same size, and the structure is plain structure. The F1, F2, F3 and F4 parts are the back hem segments, and the four parts are equal in size, and they are 2 × 2 rib structure. In the pattern shown in Fig. 4, the size of a certain section is digitally encoded, and the corresponding size name and measurements are shown in Table 1.

In this experiment, the analysis began with the actual knitted fabric and simulated the size of the real skirt knitted by the four-needle bed computer flat knitting machine (Table 1) and the actual fabric was simulated as references. The actual images of the two skirts are shown in Fig. 5. Figure 5a shows the actual image of the hip skirt, Fig. 5b shows the actual image of the umbrella skirt. The waist and hem of the skirt in the actual image are 2 × 2 rib, and the skirt part is plain structure. The approach proposed in this study differs from the traditional texture mapping method in that it can be used to simulate knitted fabrics. A simulation based on the loop unit structure was used to show the unique loop threading relationship of knitted fabrics, and simulations of different skirt surfaces based on the loop structure were performed.

Simulation of the knitted skirt based on the loop structure

Through the study of clothing modelling simulation, it was found that the data of the flat plate model and the three-dimensional surface model of the same garment in OBJ format contain vertex coordinates, normal vectors and triangle indices. The data sizes of the flat plate model and the surface model were the same, the triangle indices were the same, and only the values of the vertex coordinates and normal vectors were different (Luo et al., 2021). This principle was also followed when the knitted skirt was transformed from a flat model to a surface model. The specific research route of knitted skirt simulation based on a loop structure is shown in Fig. 6. Figure 6 shows the research route. First, the data required for simulation were obtained. Second, the spatial matrix was used to calculate the spatial transformation relationship of each pair of triangles in the plate and surface models, the triangular index of the knitted grid point in the triangularly divided flat model, and the position of the knitted grid point in the triangle of the surface model. Then, the three-dimensional coordinates of the loop type value points were obtained. Finally, combined with the process parameters of the knitted skirt, the three-dimensional clothing surface model was matched with the three-dimensional human body to simulate clothing based on the loop structure.

According to the style information of the fully-fashioned knitted skirt and the size of the three-dimensional human body, a two-dimensional pattern was drawn in the ET software, and the obtained pattern was exported as a DXF file. The DXF file was imported into the CLO3D software, and the three-dimensional human body was imported into the CLO3D.

CLO3D is a three-dimensional virtual fitting software mainly used in the clothing and textile industry (Choi, 2022; Liu et al., 2022). The software can be used to not only evaluate clothing fittings but to also output the two-dimensional DXF format model into a flat OBJ format model containing many triangular meshes. The triangular mesh was the basis of the three-dimensional model surface. By transforming the triangular meshes one by one, the shape of the three-dimensional surface model was simulated more accurately. The flat plate model composed of triangular meshes was exported as OBJ file format, and the knitted skirt surface model after virtual try-on was exported as OBJ file format, and then the flat plate model and surface model were exported as OBJ files and subsequently stored in the database of the developed knitting simulation program.

In the process of transforming the flat garment model into a curved garment model, the vertices of the triangular mesh changed, and the shape of the triangle also changed. However, the index value remains unchanged. By reading the vertex position information of the triangles with the same index value in the OBJ format file of the flat model and the surface model, the triangular facets in the OBJ file of the flat model were spatially transformed one by one to convert them to the position of the triangular facets in the OBJ file of the surface model. The spatial change of a triangle patch in the back piece of a skirt was taken as an example to illustrate the two-dimensional to three-dimensional conversion method. Where △MQU was the triangle in the flat model of the skirt, and △M'Q'U' was the corresponding triangle in the surface model of the knitted skirt. Two matrices were used to represent the triangles before and after the change: ***A*** represented △MQU, and ***B*** represented △M'Q'U'. N was set to be a unit vector perpendicular to the vectors *MQ* and *MU*, the normal vector of the triangle △MQU. Point V was the knitted grid point in △MQU. N' was set to be the unit vector perpendicular to the vectors *M'Q'* and *M'U'*, and N' was the normal

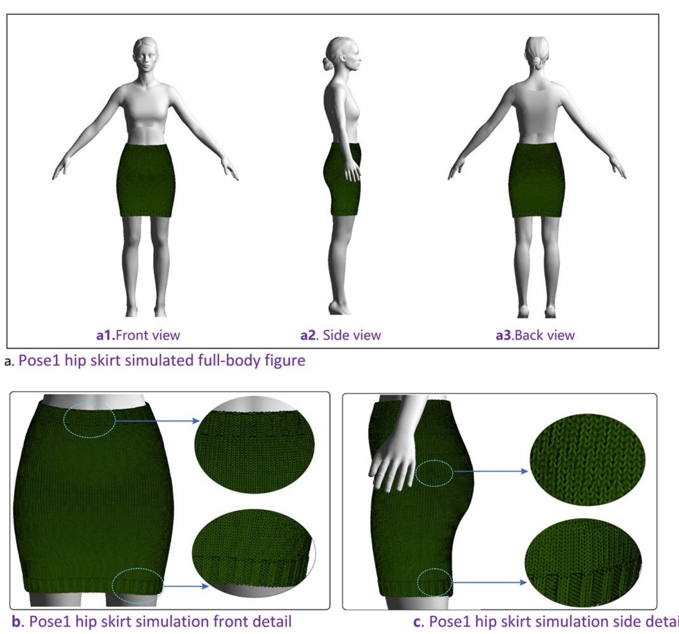
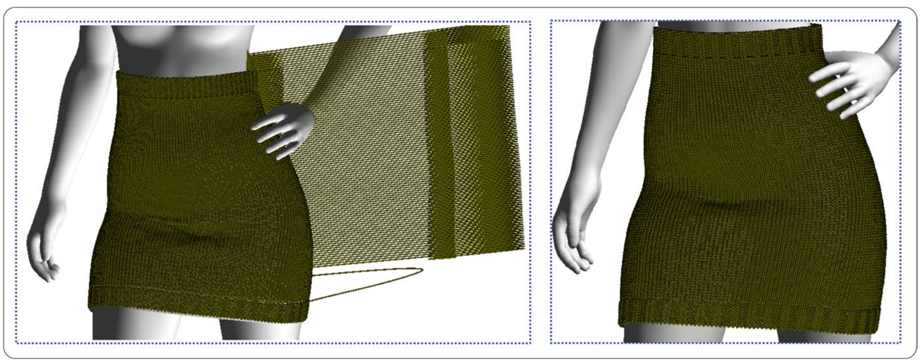


Fig. 7 Pose1 hip skirt dress simulation: **a** Pose1 hip skirt simulated full-body figure; **b** Pose1 hip skirt simulation front detail; **c** Pose1 hip skirt simulation side details

Table 2 Different postures of the same human body

Name of posture	Pose1	Pose2	Pose3	Pose4
Posture				



a. Loop drawing dislocation diagram **b.** Loop drawing correct location diagram

Fig. 8 Loop drawing diagram: **a** loop drawing dislocation diagram; **b** loop drawing correct location diagram

vector of the triangle △M'Q'U'. Point V' was the knitted grid point in △M'Q'U'. The spatial variation matrices of ***A*** and ***B*** in spatial variation were as follows:

$$A=\begin{bmatrix}\overrightarrow{MQ}.x & \overrightarrow{MU}.x & \overrightarrow{Q}.x & \overrightarrow{M}.x\\ \overrightarrow{MQ}.y & \overrightarrow{MU}.y & \overrightarrow{Q}.y & \overrightarrow{M}.y\\ \overrightarrow{MQ}.z & \overrightarrow{MU}.z & \overrightarrow{Q}.z & \overrightarrow{M}.z\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{5}$$

$$B=\begin{bmatrix}\overrightarrow{M'Q'}.x & \overrightarrow{M'U'}.x & \overrightarrow{Q'}.x & \overrightarrow{M'}.x\\ \overrightarrow{M'Q'}.y & \overrightarrow{M'U'}.y & \overrightarrow{Q'}.y & \overrightarrow{M'}.y\\ \overrightarrow{M'Q'}.z & \overrightarrow{M'U'}.z & \overrightarrow{Q'}.z & \overrightarrow{M'}.z\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{6}$$

$$\overrightarrow{N}=\overrightarrow{MQ}\times\overrightarrow{MU} \tag{7}$$

$$\overrightarrow{N'}=\overrightarrow{N}\Big/\left\|\overrightarrow{N}\right\| \tag{8}$$

The spatial variation matrix ***T*** can be calculated by matrix ***A*** and matrix ***B***, and $\boldsymbol{B^{-1}}$ is the inverse matrix of matrix ***B***. The calculation formula of T is as follows (9):

Algorithm 1: Solve loop drawing errors

Input: DXF format template L that key point n_i belongs to, Plate Model G that key point m_i belongs to, n_1 is the key point at the lower left of L, m_1 is the key point at the lower left of G

Output: Modified m_i and translation G

if $n_1 \neq m_1$ **then**

  $Differences\ n_1 m_1 = n_1 - m_1$;

  $Modified\ m_i = m_i + n_1 m_1$;

return G ;

final ;

Fig. 9 Algorithm1-Solve loop drawing errors

Table 3 Simulation times for different postures of the hip skirt

Running time/posture	Hs-pose1	Hs-pose2	Hs-pose3	Hs-pose4
Read data	18	24	23	22
Meshing grid	8	8	8	8
Spatial transformation	5230	5720	5709	5690
Draw the loop	4728	5080	5070	4998
Render	2376	2556	2525	2496
Total time	12,360	13,388	13,335	13,214
Unit: ms				

$$T = A \times B^{-1} \tag{9}$$

By multiplying the change matrix $\boldsymbol{T}$ by the column vector of point V, the coordinates of the changed V' can be obtained.

Based on the above conversion relationship, the positions of the grid points in the triangular patch of the surface model were calculated, the three-dimensional coordinates of the loop-type value points were obtained, and a loop drawing was carried out. The human body model in the database was matched with the knitted skirt surface model to simulate the knitted skirt wear simulation based on the loop structure. The loop material was created by the PBR method, and the solid section of the yarn is the prototype. After rendering, textures similar to those of natural yarn effect was generated. As shown in Fig. 7, the Pose1 three-dimensional human body dress simulation results were presented. In Fig. 7a, the Pose1 hip skirt simulation body diagram showed the overall effect of the hip skirt simulation; In Fig. 7b, the morphological characteristics and organizational structure of the loop were clearly observed in the simulated front detail of the Pose1 hip skirt. The 2 + 2 rib structure was used in the waist and hem, and the main part of the garment was plain structure. Figure 7c shows the Pose1 hip skirt simulation. Moreover, the side was clearly shown to be affected by narrowing, which produced the transfer structure.

Multi-pose dress simulation According to the literature (Cheng et al., 2018; Xu et al., 2019), four commonly used human postures, as shown in Table 2, were selected for dress simulations.

When selecting different postures for dress simulations, the shape of the knitted skirt surface model may deform, resulting in specific knitted mesh points not finding the corresponding triangular surface. This was especially true for mesh points at the edge of the template, which often could not be used to locate the index value of the triangular surface used, causing the loop to be drawn at the wrong position. Figure 8a illustrates the diagram of loop dislocation.

There were two reasons exist for the misalignment of loop drawing in different postures of human body simulated knitted skirts. The first reason was that the corresponding triangular patches could not be found in the non-edge-knitted mesh points. The second reason was that the related triangular patches could not be found in the edge-knitted mesh points. Given the misalignment of non-edge grid points, the Z-axis coordinates of the vertex coordinates of the triangular patches on the OBJ format plate model were all zero. The overall coordinates of the modified OBJ format plate model were made consistent with the two-dimensional template coordinates of the DXF format so that the corresponding triangular patches could be found on the two-dimensional template knitting grid points of the DXF format. The program adjusted the X and Y axis coordinates of the OBJ format plate model to match those of the DXF format template, both of which were in the same coordinate system. Figure 9 illustrates the Algorithm1-Solve loop drawing errors. Algorithm 1 was as follows: The DXF format two-dimensional template $\boldsymbol{L}$, the key point $\boldsymbol{n_i}$ coordinates (x_{ni}, y_{ni}), and the key point $\boldsymbol{n_1}$ coordinates with the smallest coordinate value (x_{n1}, y_{n1}) were read. The OBJ format plate model $\boldsymbol{G}$, the key point $\boldsymbol{m_i}$ coordinate (x_{mi}, y_{mi}), and the key point $\boldsymbol{m_1}$ coordinate (x_{m1}, y_{m1}) with the smallest coordinate value in the lower left corner were read; The differences between the $\boldsymbol{n_1}$ and $\boldsymbol{m_1}$ coordinates $\boldsymbol{n_1 m_1}$ (x_{n1m1}, y_{n1m1}) were calculated, and add $\boldsymbol{n_1 m_1}$ was added to all key points of the OBJ format plate model to complete the translation of the OBJ format plate model.

To address the issue of displaced edge mesh points, we had adjusted the coordinates of the knitting mesh points and recalculated the index value for the triangular patch. Figure 8b shows the simulated knitted skirt after the modified loop error. The loop was now correctly positioned and no loops were flying out.

Results and Discussion

Due to the complex threading structure between the loops in knitted garments, the simulation of knitted garments in the existing research had been based on the texture mapping method, or meshed on a three-dimensional surface and filled with different loops. The texture mapping method did not reflect the three-dimensional sense of the threading of the knitted structure, and the surface loop drawing based on the mesh division takes much time. In this study, the loop structure was drawn by two-dimensional and three-dimensional matrix transformation, which quickly simulated knitted garments based on the loop structure on complex wrinkled surfaces formed by different postures.

The modelling was performed on a system with a 12th Gen Intel(R) Core(TM) i9-12900H, 2.50 GHz, 16 GB RAM, and Legion Y9000PIAH7H running on Windows

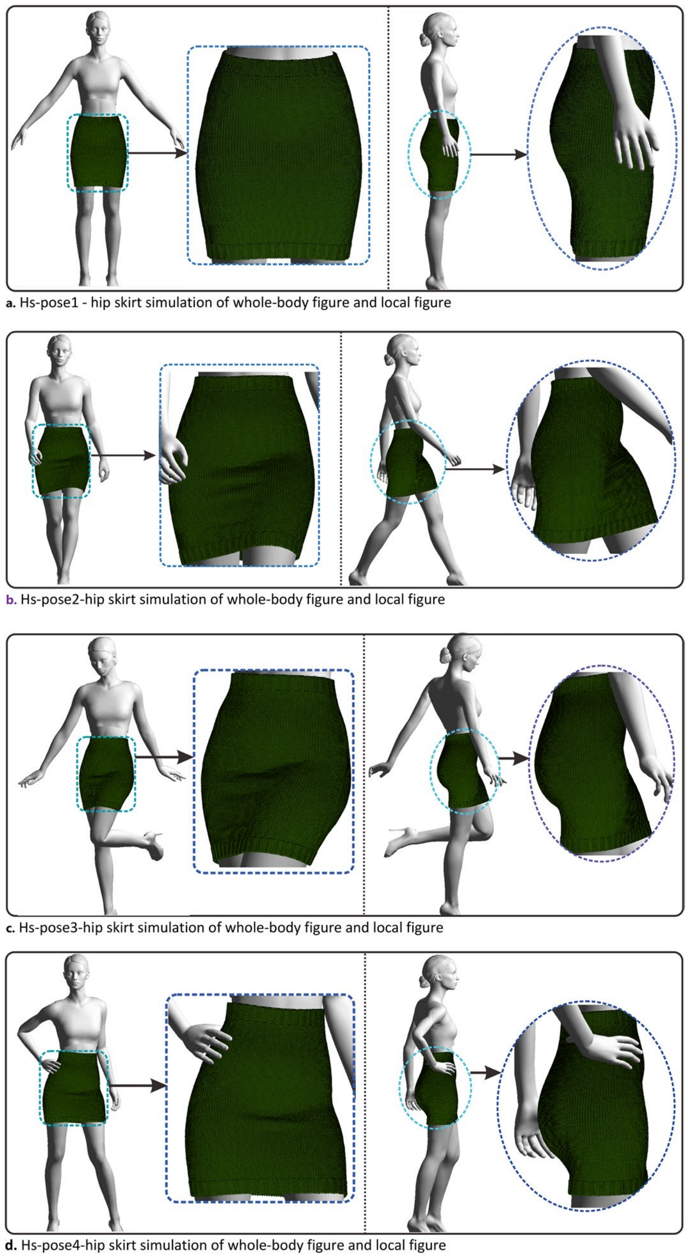


Fig. 10 Multi-pose simulation of the whole body and local figure of the hip skirt: **a** Hs-pose1-hip skirt simulated whole body and local figure; **b** Hs-pose2-hip skirt simulated whole body and local figure; **c** Hs-pose3-hip skirt simulated whole body and local figure; **d** Hs-pose4-hip skirt simulated whole body and local figure

11OS. The software platform used was the Microsoft Visual Studio 2022, which integrated development tools with the OpenGL 3D graphics library.

The above method was used to program the multi-pose dress simulation of the hip skirt in the knitted skirt. Table 3 displays the simulation times for various hip skirt (Hs) postures. From Table 3, we could see that the total simulation time of posture 1 was the shortest, which was 12,360 ms. The total simulation times of the hip skirts of Hs-pose2, Hs-pose3, and Hs-pose4 were close to each other, all of which were approximately 13 s.

Table 4 Simulation times for different postures of umbrella skirts

Running time/posture	Us-pose1	Us-pose2	Us-pose3	Us-pose4
Read data	31	33	32	32
Meshing grid	8	8	8	8
Spatial transformation	6598	7278	7293	7256
Draw the loop	6128	7128	7121	7098
Render	5450	6520	6461	6316
Total time	18,215	20,967	20,915	20,710

Unit: ms

However, more than 80% of the simulation time was taken up by the spatial transformation and drawing the loop. Overall, simulating the four hip skirt postures was quick and took no longer than 14 s. The four different postures of the hip skirt had the same two-dimensional model, but the simulation times were different. The reason was that the shape of the triangle on the surface changes according to posture. Although the triangle index did not change, the larger morphological changes caused the loop type value point to find the corresponding triangle. It took a long time to find the corresponding triangle, so the simulation of the four postures in the simulation of the larger posture Hs-pose2 simulation time was the longest.

The whole-body and local pictures of the multi-pose simulation of the hip skirt were shown in Fig. 10. The simulated whole-body diagram and local diagram of the four postures clearly showed the rib structure of the waist of the fully formed knitted hip skirt, the plain structure in the middle of the skirt and the rib structure of the hem. Combined with Fig. 10 and Table 3, it was found that the surface of the hip skirt simulated by Hs-pose1 was smooth and wrinkle-free, so the simulation time was the shortest. The leg posture movements of Hs-pose2, Hs-pose3, and Hs-pose4 were greater than those of the other strains, which caused the skirt to form wrinkles and non-smooth surfaces. The simulation time was longer than that for smooth surfaces. However, this approach did not affect the detailed simulation of the hip skirt, and the structure of the knitting loop could still be seen from the figure of the simulation results.

To test the efficacy of the simulation method, four different positions of the umbrella skirt (Us) were simulated, and the simulation times were recorded in Table 4. From Table 4, we could see that Us-pose1 had the shortest simulation time because of its simple action, and Us-pose2, Us-pose3, and Us-pose4 had actions with large deformation ranges. Thus, their simulation times were longer. Among them, the total simulation time of Us-pose2 was the longest, but the action amplitude at the leg of Us-pose3 was larger, resulting in more irregular surfaces and affecting space conversion. Therefore, the space conversion time in the simulation step of Us-pose3 was greater than that of Us-pose2, which had the longest space conversion time among the four actions. A comparison of the total simulation times for the two skirts in Tables 3 and 4 revealed that the simulation time for the simplest posture Us-pose1 of the umbrella skirt was greater than the simulation time for the Hs-pose4 posture with the largest hip skirt posture. Because the size of the umbrella skirt was larger than that of the hip skirt template, the number of simulated loops was greater than the number of hip skirt loops, so the total simulation

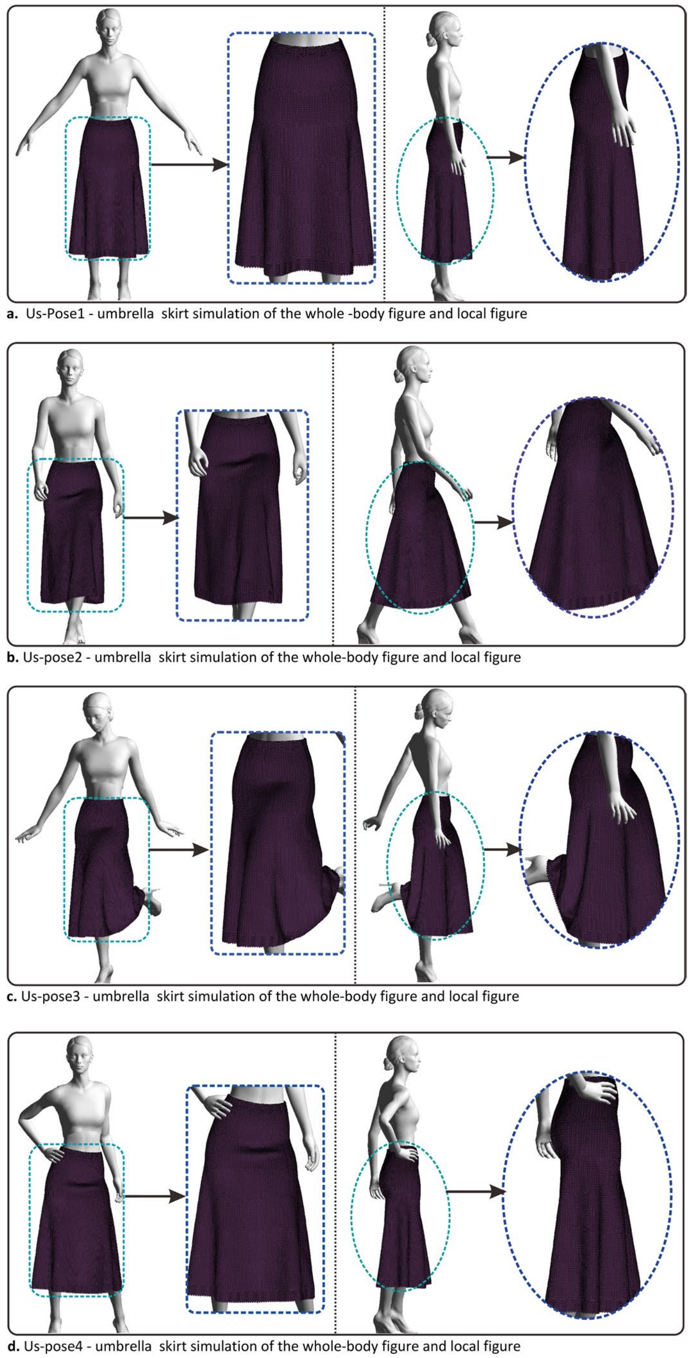


Fig. 11 Multi-pose simulation of the whole body and local figure of the umbrella skirt: **a** Pose1 umbrella skirt simulation of the whole body and local figure; **b** Pose2 umbrella skirt simulation of the whole body and local figure; **c** Pose3 umbrella skirt simulation of the whole body and local figure; **d** Pose4 umbrella skirt simulation of the whole body and local figure

time of the umbrella skirt was greater than the total simulation time of the hip skirt. The four umbrella skirts with different postures had the same two-dimensional template. However, because of the difference in the degree of triangle deformation and the number of folds on the surface formed by different postures, the simulation times were different.

The corresponding larger morphological changes and more folds will caused the loop-type point to take longer to find the corresponding triangle. Thus, the simulation time of Us-pose2 with larger deformation in the four simulated postures was the longest.

A multi-pose simulation of the whole body and a local picture of the umbrella skirt were shown in Fig. 11. The simulated whole-body figure and local figure of the four postures showed the rib structure of the waist of the fully formed knitted umbrella skirt, the plain structure in the middle of the skirt, and the rib structure of the hem. It could be seen from Fig. 11 that the skirts of the four postures of the umbrella skirt had wrinkles, and the knitting loop structure of the umbrella skirt could still be well simulated well using this method.

This program could be used to simulate a knitted skirt in multiple poses using a loop structure. This was achieved by creating a geometric model and grid model of the loops, calculating spatial transformation relationships, and drawing the loops. The program simulated both hip and umbrella skirts in four different postures. Additionally, it quickly simulated different knitted structures on the same skirt. Compared with the simulation method of He (2017), this simulation not only represented the loop structure of the plain structure, but also simulated the rib and loop structure in combination with the actual process of the knitted garment. Compared with the texture mapping method of Luo et al (2021), this simulation not only reflected the relationship between the three-dimensional fabric structure but also improved the realism of the simulation effect. Compared with the existing knitting design software such as the SDS-ONE APEX3 software of the SHIMA Company and the M1 PLUS software of the STOLL Company, this simulation realized the three-dimensional simulation of knitted skirt based on a loop structure and intuitively presented the three-dimensional knitted garments to designers and customers. This approach verified the fitness and fashion of clothing more comprehensively and intuitively, helped designers make targeted modifications and improvements, greatly shortened the development cycle and proofing times, and reduce waste.

Conclusions

This study comprehensively analyzed the structural characteristics of fully-fashioned knitted skirts and developed mathematical models for their patterns, loop geometry, and loop mesh. Utilizing spatial transformation via a matrix approach, the study accurately positioned grid points within triangular patches of surface models, facilitating the calculation of three-dimensional coordinates for loop-type value points. Employing C# and OpenGL technologies, the research successfully simulated the knitted skirt's multi-pose dressing effects based on its loop structure. Unlike traditional texture mapping methods, the proposed simulation method effectively captured the unique threading relationships inherent in knitted fabrics, enhancing realism and detail. The constructed loop models offer versatile applications for simulating various knitted garment shapes, promising intuitive product simulations that streamline design iterations and bolster production efficiency, aligning with sustainable manufacturing practices. Future research avenues include expanding simulation capabilities to encompass diverse organizational structures such as twist and inlay, further advancing the field of knitted garment simulation.

Author contributions
BC developed the research idea. BC carried out the research and drafted the first manuscript and developed programming source codes. GJ collected clothing information and made patterns and 3D garments. BL provided a lot of modification suggestions. All authors read and approved the final manuscript.

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Availability of data and materials
The data (patterns, models, 3D restored clothing, etc.) used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All the authors agree to publish.

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

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