Fibers and Polymers
https://doi.org/10.1007/s12221-025-00951-y

Online ISSN 1875-0052
Print ISSN 1229-9197

REGULAR ARTICLE

Rapid Simulation of Yarn-Level Realism in Fuzzy Yarn Knitted Fabrics

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Received: 22 July 2024 / Revised: 23 March 2025 / Accepted: 4 April 2025

Abstract

Simulation of knitted fabrics is of significant importance in the textile industry for enhancing product design efficiency and reducing prototype development costs. However, traditional yarn models often fail to precisely replicate the complex textures and physical behaviors of yarns with abundant fuzziness, which significantly compromises the realism and practical value of simulations. To overcome these limitations, this study proposes an innovative grooved ribbon yarn model that optimizes the geometric construction of yarns, enabling more accurate simulations of fuzziness inter-covering and complex physical behaviors. Utilizing physically based rendering techniques and consumer-grade imaging equipment, the proposed method effectively reduces computational and imaging costs while improving the efficiency of fabric simulation workflows. The simulation results demonstrate that the improved yarn model significantly enhances the precision of simulations, particularly in reproducing the intricate textures and structural continuity of fuzz-rich yarns, thereby offering practical value for textile design and manufacturing applications.

Keywords Fabric simulation · Fancy yarns · Grooved ribbon yarn model · Knitting · Structural simulation · Texture mapping

1 Introduction

Fuzz-rich yarns are characterized by dense fiber ends surrounding the yarn core, rendering the fabric surface soft and fluffy. This unique texture not only enhances the tactile quality of the fabric but also impacts its thermal properties, making it a desirable attribute in both apparel and home textiles. However, traditional modeling techniques struggle to capture the randomness and density of fuzz [1]. Making it crucial to develop a yarn model that accurately reflects the characteristics of knitted fabrics while accommodating industrial production speeds to enhance production efficiency and market competitiveness [2].

In the realm of knitted fabric simulation technology, using a two-dimensional loop model for texture mapping has proven to be an extremely efficient method. This model quickly reproduces the appearance of knitted fabrics using fewer computational resources [3]. By setting up the intertwining points model on the two-dimensional model's yarn center curve and combining it with cubic Bézier curves to fit the loops, and then through texture mapping, interpolation, and brightness adjustment, an accurate simulation of the knitted texture is achieved [4]. This method not only significantly boosts the efficiency of the simulation rendering but also, while ensuring visual realism, is suitable for rapidly and precisely simulating the tactile feel of standard yarn-knitted fabrics [5]. Due to the model's two-dimensional nature, this method might not fully capture depth and detail and may not achieve the visual effects of advanced three-dimensional simulation techniques when dealing with complex light and shadow interactions.

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Published online: 09 May 2025

To precisely reproduce the surface details of the yarn, a method of deforming the cylindrical structure of the yarn into an elliptical cross-section was adopted, followed by projecting this cross-section onto a two-dimensional plane [6]. Subsequently, the yarn image is adjusted to fit the dimensions and shape of the elliptical cross-section. Then, through preprocessing and applying elastic and geometric transformations, combined with light intensity curve models and Boolean matrices, the three-dimensional shape and varying light effects of the yarn are accurately reproduced on the two-dimensional plane, visually expressing the yarn's three-dimensionality authentical [7, 8]. For colored fabrics, by assuming the yarn as a smooth cylinder, the constructed geometric and color mixing models can predict the final color of the woven fabric made from colored yarns. The intertwining and bending of the yarn in the fabric affect its visual length representation, and by adjusting coefficients to modulate its length, and setting offsets and offset rates to simulate the yarn's random bending, a more realistic three-dimensional yarn form is achieved [9]. Based on the tubular yarn model, the loop model can be constructed in conjunction with a mass-spring model to predict the deformation behavior of cable knit fabrics. Using particle swarm optimization algorithms and FAST testing methods, the parameters of the mass-spring model in the knitted fabric simulation are optimized, effectively simulating the draping behavior of different types of knitted fabrics [10, 11]. To further enhance the realism of the simulation, by adapting the tubular structure model to different types of fibers, the microstructure of the yarn is detailedly simulated, and designers are allowed to adjust the fluffiness of the yarn and the irregularity of the loop positions, making the knitted garments rendered with a realism that closely resembles the complexity and delicate texture [12, 13]. Although the tubular model is effective in basic fabric simulations [14], it is limited in scenarios requiring highly complex and detailed simulations due to simplified yarn mapping processes.

For more in-depth realism and detail, the research tends to adopt more advanced simulation techniques. Procedural model fitting technology provides a method to precisely reproduce the physical and visual properties of yarns, particularly effective in simulating complex effects of lighting and shadows on yarns [15, 16]. This technology enables users to optimize the visual presentation of yarns by adjusting various parameters, thereby enhancing the rendering realism of yarns and fibers [17]. This method is based on the Bi-Directional Scattering Distribution Function (BCSDF) of textile fibers, employing precomputed light transport techniques to enhance rendering efficiency and more accurately express the physical properties of fibers [18]. However, obtaining sufficiently detailed yarn data usually relies on high-cost, operationally complex technologies such as CT scans, increasing the economic burden and technical difficulty of the simulation [19, 20]. Moreover, achieving specific visual effects of the yarn might require multiple trials and adjustments, not only consuming substantial computational resources but also adding complexity to the simulation process.

To address the limitations of existing fuzzy yarn-knitted fabric simulation methods, this study proposes an innovative yarn-knitted fabric simulation framework. First, in response to the inability of traditional tubular yarn models to accurately simulate the fuzz coverage effect and its interactions in three-dimensional space, a novel grooved ribbon yarn model is introduced. This model enables a more precise representation of the microstructure of fuzzy yarns, particularly when simulating yarns with a stronger fuzz effect, exhibiting a more complex and intricate structure that significantly enhances the visual realism of the simulation results. Second, considering the limitations of traditional high-cost imaging equipment, this study innovatively employs consumer-grade camera devices for image acquisition. This approach not only ensures the visual representation of the yarn is maintained but also significantly reduces costs, while improving the operational convenience of the technology, thus enhancing its applicability in real-world textile industry settings. Lastly, to further improve the computational efficiency of large-scale fabric simulations, this study introduces a simulation method based on periodic replication. By periodically replicating portions of the fabric model and avoiding the need to generate each individual loop, this method significantly accelerates the simulation process. This innovative approach reduces simulation time without sacrificing quality, making real-time fabric rendering and dynamic simulation feasible.

2 Existing Problems in the Research

The characteristics of yarns with rich fuzziness are manifested by the protrusion of fiber ends from the core yarn, which displays significant randomness in length, direction, and density. This structural complexity leads to intricate light scattering and absorption behaviors on the fabric surface, enhancing the visual and tactile appeal of textiles, as illustrated in Fig. 1a. Furthermore, the presence of fuzziness conceals the basic loop structures of knitted fabrics, posing substantial challenges in accurately simulating these effects in yarn-knitted fabrics, as shown in Figs. 1b and c.

Currently, tubular yarn models commonly used in the simulation of knitted fabrics with rich fuzziness often overlook the details of fuzz, resulting in a significant discrepancy between the simulated and actual fabrics, as depicted in Fig. 1d. Moreover, the fuzz generation based on fabric models also shows a considerable difference from the actual fabrics, and this method consumes a substantial amount of

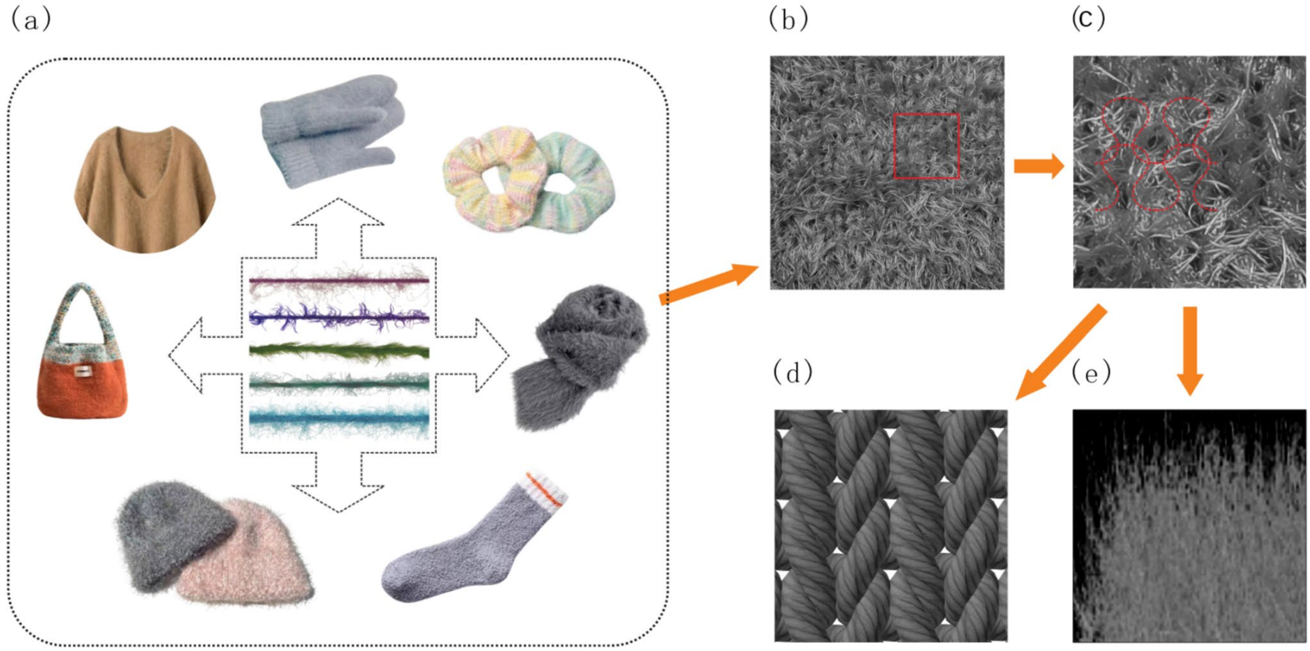

Fig. 1 Challenges in simulating knitted fabrics with richly fuzzy yarns: **a** Applications of richly fuzzy yarns and their products, **b** Knitted fabric with richly fuzzy yarn, **c** Detail of knitted fabric loops, **d** Simulation results using tubular yarn models, **e** Fuzz generation based on fabric models

computational resources, with the effects demonstrated in Fig. 1e.

3 Yarn Texture Processing

To address the challenges of simulating knitted fabrics with richly fuzzy yarns, this study proposes the use of a grooved ribbon yarn model, combined with physically based rendering (PBR) techniques, to simulate the realistic textures of yarns. In this process, high-quality image processing is crucial not only for replicating the authentic appearance of the yarn but also for achieving an efficient rendering process.

3.1 Yarn Image Acquisition and Processing

To enhance the efficiency and cost-effectiveness of yarn image acquisition, this study utilized consumer-grade smartphone cameras as the primary tool, replacing expensive and operationally complex CT scanning technologies [21]. This low-cost and easy-to-operate method significantly lowers the technical and economic barriers to image acquisition, reducing reliance on professional equipment and facilitating the transition from laboratory techniques to industrial applications.

In this research, the preprocessing of actual yarn images began with capturing raw yarn images using consumer-grade smartphone cameras. Initially, the images were cropped to focus on the yarn and eliminate unnecessary background elements, ensuring that only the areas directly related to the yarn were processed. To emphasize the yarn's main body, a binarization process was applied by setting a threshold T, where pixel values greater than or equal to T were set to 1, and those below T were set to 0. Through this method, we effectively extracted regions containing only the yarn from the original images, while excluding the background, as shown in Fig. 2b.

Further, determining the minimum repeat unit of the yarn texture was a step crucial for ensuring the continuity and consistency of yarn maps during rendering, especially

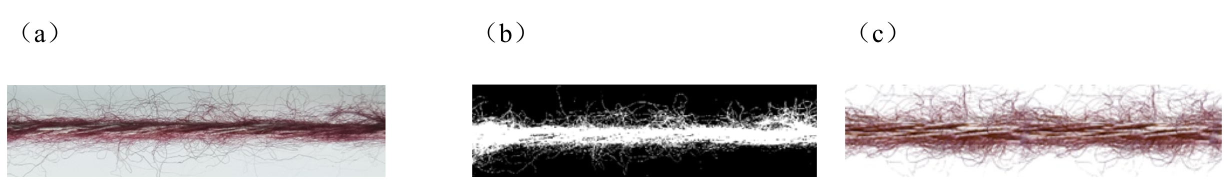

Fig. 2 Yarn image processing. **a** Original yarn image, **b** Binarized yarn image, **c** Bi-directionally continuous yarn texture image

important in large-area rendering. This unit was selected based on the natural repeating pattern of the yarn texture, identifying an area that could seamlessly repeat without visible boundaries or inconsistencies. Finally, ensuring these texture units achieved bidirectional continuity on the horizontal axis was essential to ensure seamless integration at the seams when applied on three-dimensional models, preventing breaks or repetitions and thus visually creating a continuous and realistic surface effect, as shown in Fig. 2c. These processing steps collectively ensured the accurate and authentic representation of the yarn's physical and visual properties during rendering.

To better simulate the texture and surface characteristics of the yarn, data from the yarn image preprocessing stage was converted into keymaps, including albedo, roughness, and metalness maps. These maps describe the material's base color, surface roughness, and reflectivity, respectively, and are indispensable components of the PBR technique. Height maps enhanced the texture's three-dimensionality and detail depth, while opacity maps defined visible areas of the yarn and ambient occlusion maps improved local shadow effects. These components collectively enhanced the overall visual realism.

3.2 Calculation of Yarn Diameter Based on Yarn Images

In fabric simulation, the visual diameter of yarns is significantly influenced by the length of the fuzz, even though the core diameter of the yarn may remain consistent. This implies that even if two yarns have the same actual core diameter, differences in fuzz length can make them appear to have different diameters visually, leading to potential mismatches when applying yarn texture images for mapping, as shown in Fig. 3. To address this challenge, this study developed an automatic diameter calculation method based on yarn opacity maps. This method adjusts the visual diameter of the yarn by analyzing changes in opacity within the yarn opacity maps, ensuring that the yarn model's diameter remains visually consistent even with varying lengths of fuzz, thus enhancing the accuracy of the simulation mappings and the overall visual effect.

Based on the yarn opacity map, the pixels in the yarn image can be simply classified into transparent and non-transparent pixels. The non-transparent pixels consist of two main components: the yarn core and the fuzz. This relationship can be expressed as:

$$N \times A = X + Y \tag{1}$$

where N is the total pixel count, A is the opacity ratio of the yarn portion, X is the pixel count of the yarn core, and Y is the pixel count of the fuzz.

The number of fuzz pixels, Y, can be approximated as:

$$Y \approx (N - X) \times C \tag{2}$$

where C denotes the proportion of non-transparent pixels (i.e., fuzz) relative to the total pixels in the row of the opacity map's auxiliary line, as shown in Fig. 4. The fuzz pixel count is then estimated by multiplying the remaining pixels, excluding the yarn core, by C. Based on this, the equation is established:

$$N \times A \approx X + (N - X) \times C \tag{3}$$

where the values of N, A, and C can all be obtained from the image. By removing the fuzz pixels from the total non-transparent pixels, the number of yarn core pixels X can be determined. Next, the yarn core diameter r is estimated by calculating the proportion of yarn core pixels relative to the total image pixels and multiplying by the image height H:

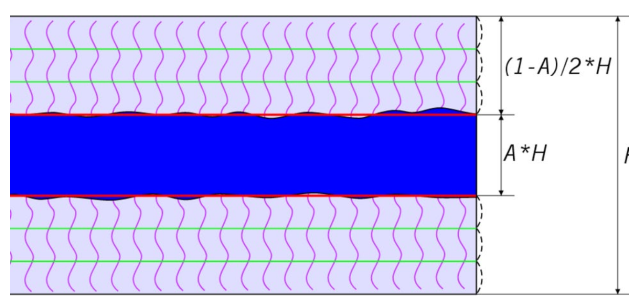

Fig. 4 Guide line positions

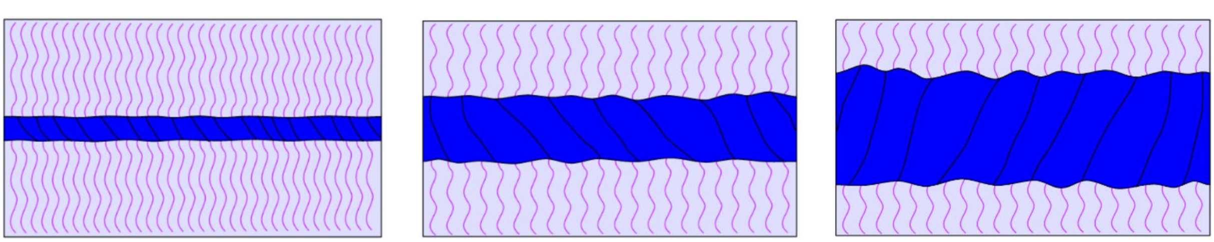

Fig. 3 Yarn images of the same size with different yarn diameters

$$r \approx \frac{H \times X}{2} \tag{4}$$

This method ensures that the diameters of the yarn core and fuzz regions in the image correspond precisely to the diameters of the core and fuzz regions in the yarn model. This correspondence not only guarantees the accuracy of the geometric dimensions but also significantly enhances the visual realism of the simulation model, making it more aligned with actual conditions and improving the model's practical application value.

4 Fabric Model

Our research employs a three-dimensional geometric model based on a grooved ribbon structure, which is highly compatible with the texturing processes of yarn images, significantly enhancing data processing speed. With this three-dimensional ribbon model, we are able to precisely replicate the length, width, and depth of the yarn in space, thereby more accurately simulating its physical properties.

4.1 Yarn Modeling

The arrangement of yarns in fabrics displays highly complex interaction patterns, not merely simple alignment or overlapping. Figure 5a illustrates the cross-sectional state of adjacent yarns when interlaced, Fig. 5b shows how the fuzz of adjacent yarns covers the core of the yarn before it, and Fig. 5c demonstrates the simplified cross-section of the yarn form unaffected by fuzz, as well as how fuzz overlaps between yarns. This complex interaction pattern requires that our model not only reproduce the basic geometric shapes of the yarn but also capture the interactions between the yarn fuzz.

To more realistically simulate these complex physical behaviors, the yarn model's cross-section was initially set as a straight line, as shown by the green line in Fig. 6a. However, this smooth ribbon model's cross-section only simulates the fuzz coverage in one direction and fails to achieve comprehensive overlap between the fuzz.

To overcome the limitations of fuzz coverage, adjustments were made to the fuzz part of the smooth ribbon yarn model, allowing it to incline towards the front of the yarn core. For the scientific simplicity and practicality of the model, the yarn's cross-section was designed as an equilateral hexagon. This design leverages the symmetry and straight-edge characteristics of the hexagon, enabling a more natural simulation of the fuzz extension in front of the yarn core while reducing the complexity of boundary calculations during simulations. Figure 6b shows the state of the cross-section in the grooved ribbon yarn model, where the fuzz parts extend along the edges of the hexagon according to their length, as depicted in Figs. 6d, e, and f. The theoretical width (i.e., the diameter of the yarn) differs from the actual width (i.e., the texture width of the yarn), necessitating a comprehensive consideration of these two dimensions in the grooved ribbon yarn model. In this model, the yarn diameter is denoted as $2r$, and the entire yarn texture actual width is marked as H. The distance from the edge of the yarn core to the edge of the yarn cross-section represents the width of the yarn fuzz. This design not only ensures the geometric accuracy of the model but also allows the fuzz to correctly simulate its coverage effect on adjacent yarns in simulations. As shown in Fig. 6f, by inclining the fuzz parts, the fuzz can more naturally cover adjacent yarns in three-dimensional space, simulating the real-world interactions of yarns.

4.2 Loop Model Improvement

In this study, the path of the fabric loops is modeled using third-order NURBS curves, with each loop defined by nine

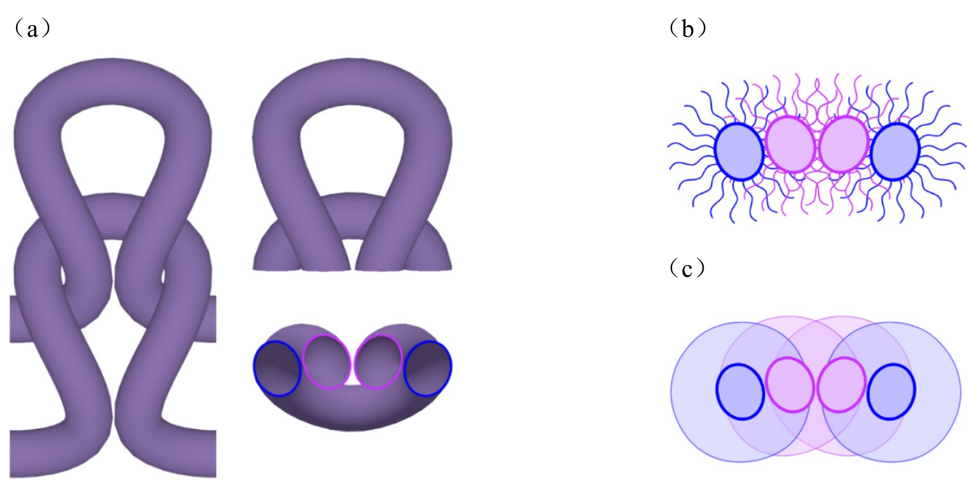

Fig. 5 States of yarn in the fabric: **a** position of yarns in the fabric; **b** fuzz states of adjacent yarns

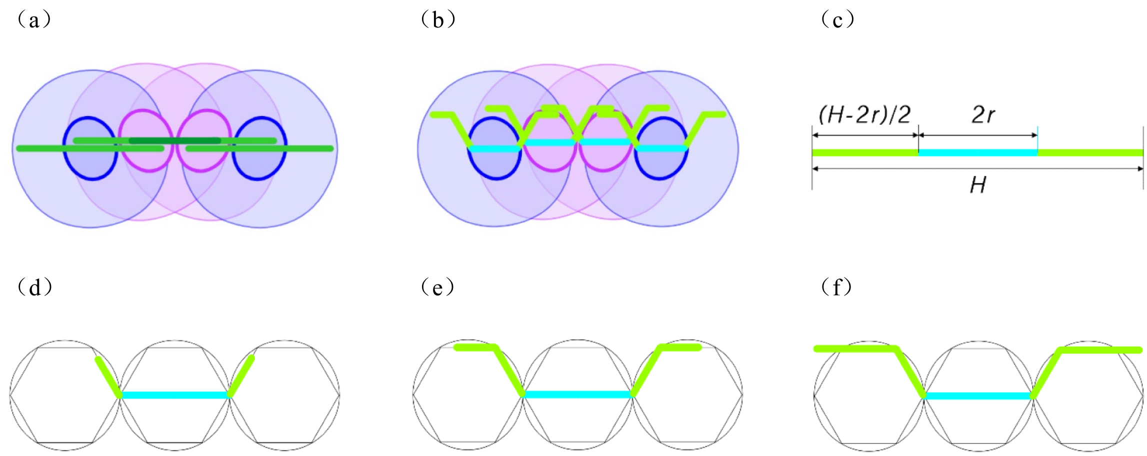

Fig. 6 Cross-sections of the yarn models: **a** Cross-section of the ribbon yarn model, **b** Cross-section of the improved ribbon yarn model, **c** Data for the cross-section of the improved ribbon yarn model, **d**, **e**, **f** Cross-sections of yarn models with the same diameter but different fuzz lengths

control points (P_1–P_9) [22], as shown in Fig. 7. Among these control points, the top contains one key point, which defines the upper boundary of the loop arc; the bottom contains two key points, which define the left and right boundaries as well as the lower boundary of the loop arc; and the middle control points define the specific shape of the loop. The loop models

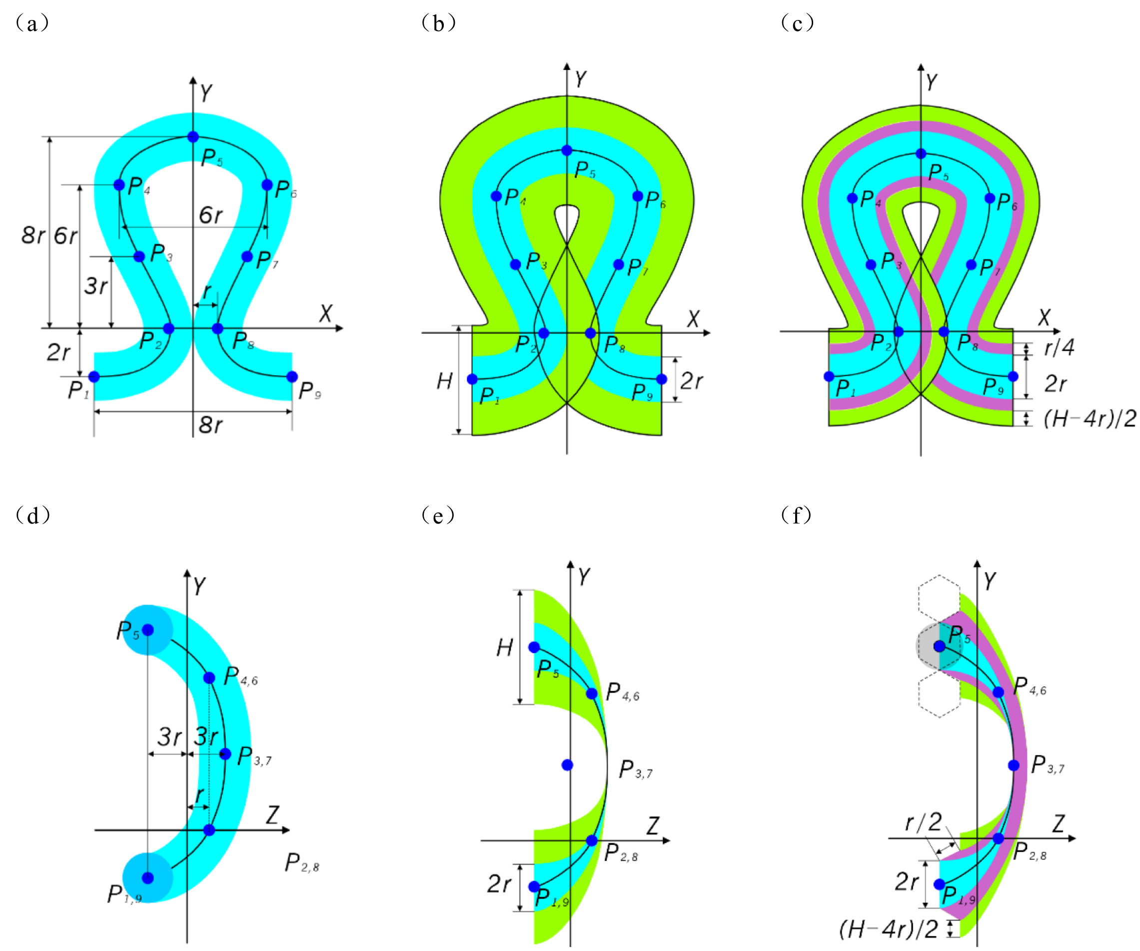

Fig. 7 Comparison of loop models based on tubular, ribbon, and improved ribbon yarn models: **a**, **b**, **c** front views; **d**, **e**, **f** left views

for the tubular and smooth ribbon yarn models are based on the same path; the former only reflects information about the yarn core, as shown in Figs. 7a and d, while the latter includes information about both the yarn core and the fuzz, with the fuzz parts overlapping in the sagging arc sections of the loops, as depicted in Figs. 7b and e. A comparison of the two models shows that while the yarn core shapes appear consistent when viewed from the front, the smooth ribbon yarn model increases the loop width by incorporating fuzz parts. However, from a side view, due to differences in the structure of the yarn models, their visual representations differ. The smooth ribbon yarn model, due to its lack of volume, shows a line-like appearance in the side view when the path changes along the Z-axis are minor; when the path changes more significantly along the Z-axis, the side view appears more planar, as demonstrated in Fig. 7e.

Furthermore, the loop model of the grooved ribbon yarn builds upon the smooth ribbon yarn model by extending the fuzz along the edges of a simplified hexagon near the main yarn cores, as shown in Figs. 7c and f. From the frontal perspective, the core shapes of both models appear consistent, but the grooved ribbon yarn model, with its fuzz inclined towards the positive Z-axis, has a slightly narrower width than the smooth ribbon yarn model, as shown in Fig. 7f. Additionally, the side view of the loop model illustrates increased thickness.

4.3 Fabric Model Construction

In this study, the loop model was constructed using NURBS (Non-Uniform Rational B-Splines) curves in three-dimensional space as the generating paths, defined by nine control points for each loop. Specifically, a k-degree NURBS curve is represented as a piecewise rational polynomial vector function defined as:

$$C(u) = \frac{\sum_{i=0}^{n} N_{i,k}(u) w_i A_i}{\sum_{i=0}^{n} N_{i,k}(u) w_i} \tag{5}$$

where $N_{i,k}(u)$ are the kth-degree standard B-spline basis functions computed from the knot vector $U = [u_0, u_1, \cdots, u_{n+k+1}]$, w_i are the weights, and A_i are the control points that together determine the curve's geometric shape and spatial layout. Since the last control point of each loop coincides with the first control point of the next, each loop in the fabric model effectively consists of eight control points. The loop configuration is illustrated in Fig. 8a and b, where the blue parts represent the yarn core, and the green parts represent the yarn fuzz.

After establishing the individual loop model, the next task is to arrange these loops according to the specific pattern of weft-knit organization. In weft-knit structures, loops are arranged horizontally, with each loop not only connected to its adjacent loops on the left and right but also interlaced with the loops in the rows above and below, thus forming the complete fabric structure as shown in Figs. 8c and d. Due to the unique features of the grooved ribbon yarn model, the visibility of the yarn core in the fabric is determined by the length and density of the yarn fuzz, significantly enhancing the visual realism of fuzz-rich knitted fabrics. This model accurately captures the details of the yarn core and its fuzz, thus realistically reflecting the physical and visual properties of the yarn within the fabric.

5 Fabric Simulation Implementation

This study's simulation and rendering of yarn and fabric were conducted on a Windows 10 system equipped with an Intel Core i5-13600 KF CPU and 32 GB RAM.

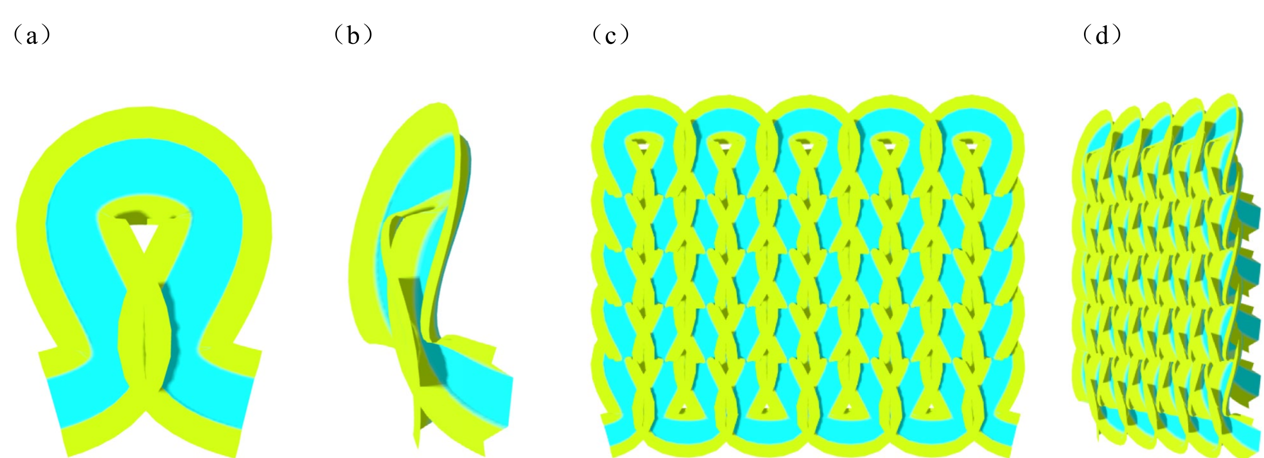

Fig. 8 Loop models and weft-knit fabric models generated using the grooved ribbon yarn model: **a** front view of the loop model, **b** side view of the loop model, **c** front view of the fabric model, **d** side view of the fabric model

All programming was completed using JavaScript and performed through WebGL technology supported by the THREE.JS library.

5.1 PBR Texture Rendering

For the visual simulation of textiles, this research utilized PBR technology, which provides a more precise and realistic simulation approach compared to traditional simplified lighting models and texture mapping methods. This method renders based on the microsurface structure of materials and their physical properties regarding light scattering, reflection, refraction, and absorption, allowing for detailed reproduction of the gloss and texture details of textile surfaces [23, 24]. In practice, the properties of each yarn material are expressed through corresponding maps. These maps are designed based on the physical properties of the materials, ensuring that the interactions with light are accurately simulated, thereby enhancing the realism and visual depth of the rendering effects (Fig. 9).

5.2 Light and Shadow Rendering

In the 3D simulation of fabrics, the accurate configuration of the lighting model is crucial for ensuring the authentic representation of material characteristics. For this purpose, ambient light and directional parallel light sources are comprehensively used to simulate natural and artificial lighting conditions. Ambient light simulates non-directional scattered light, providing basic illumination for the scene and preventing excessive shadows. In contrast, directional light simulates sunlight or other distant light sources coming from a specific direction. It is characterized by uniform and consistent light rays, with adjustable intensity and color to accommodate different simulation scenarios and material properties. Figure 10 demonstrates the effect of various lighting conditions on the surface details of the fabric. This setup not only ensures the adaptability and flexibility of the lighting but also precisely reproduces the gloss and complex texture details of yarns and fabrics by simulating different materials'responses to reflection, refraction, and absorption of light.

In this study, the shadow processing of grooved ribbon geometries has been optimized. Due to the volume-less nature of these geometries, traditional shadowing methods can produce rippling and other artifacts during rendering. Particularly in the calculation of self-shadowing, it is crucial to precisely handle the relative positions between the light sources and the geometries, as well as the shapes of the geometries themselves, to avoid visual distortions. To address this challenge, the Variance Shadow Maps (VSM) technique was employed. This method determines whether a pixel is in shadow by analyzing the depth values and their variance, thereby creating a more natural gradient effect at the shadow edges [25]. As shown in Fig. 10d, this approach enhances the realism of the shadow transitions. The implementation of this technique leverages GPU hardware acceleration and utilizes standard 2D texture filtering techniques to smooth the shadow edges, significantly enhancing rendering efficiency.

5.3 Fabric Simulation Result

The groove ribbon yarn model utilizes the texture of real yarns, accurately reproducing the complexity and irregularity of the yarn edges, closely approximating the true physical properties of the yarn. This is particularly effective in simulating the three-dimensional appearance of hairiness and the interaction between yarns' hairiness, resulting in a more realistic simulation. However, this study primarily focuses on yarns with pronounced hairiness. For yarns with finer or less hairiness, although the model can reproduce the details of the yarn edges, the impact of hairiness on the yarn cross-sectional shape is minimal due to the finer nature of the hairiness. As a result, the simulation does not fully reflect the differences in microstructure. As shown in Fig. 10, compared to the smooth ribbon yarn model, the groove ribbon yarn model offers a more complex and refined representation of the yarn's microstructure and texture layers, particularly for yarns with longer or denser hairiness,

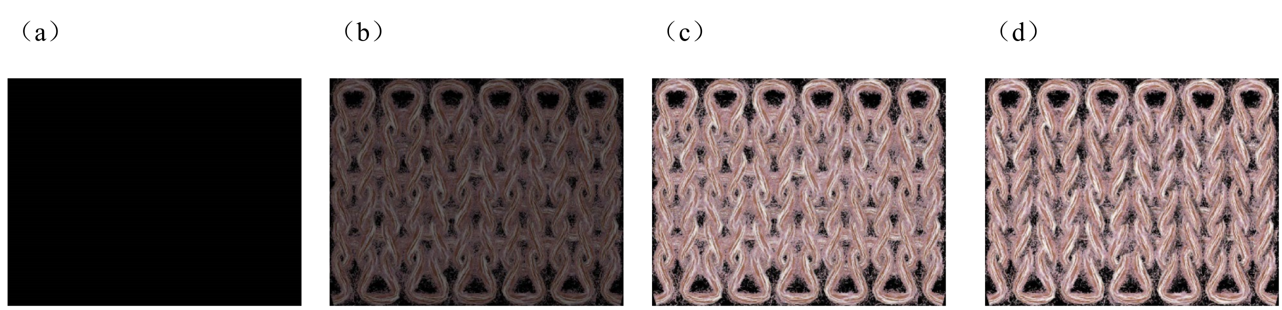

Fig. 9 Comparison of different lighting and shadow conditions: **a** No lighting, **b** Ambient lighting, **c** Ambient lighting and directional light, **d** Ambient lighting, directional light, and VSM shadow

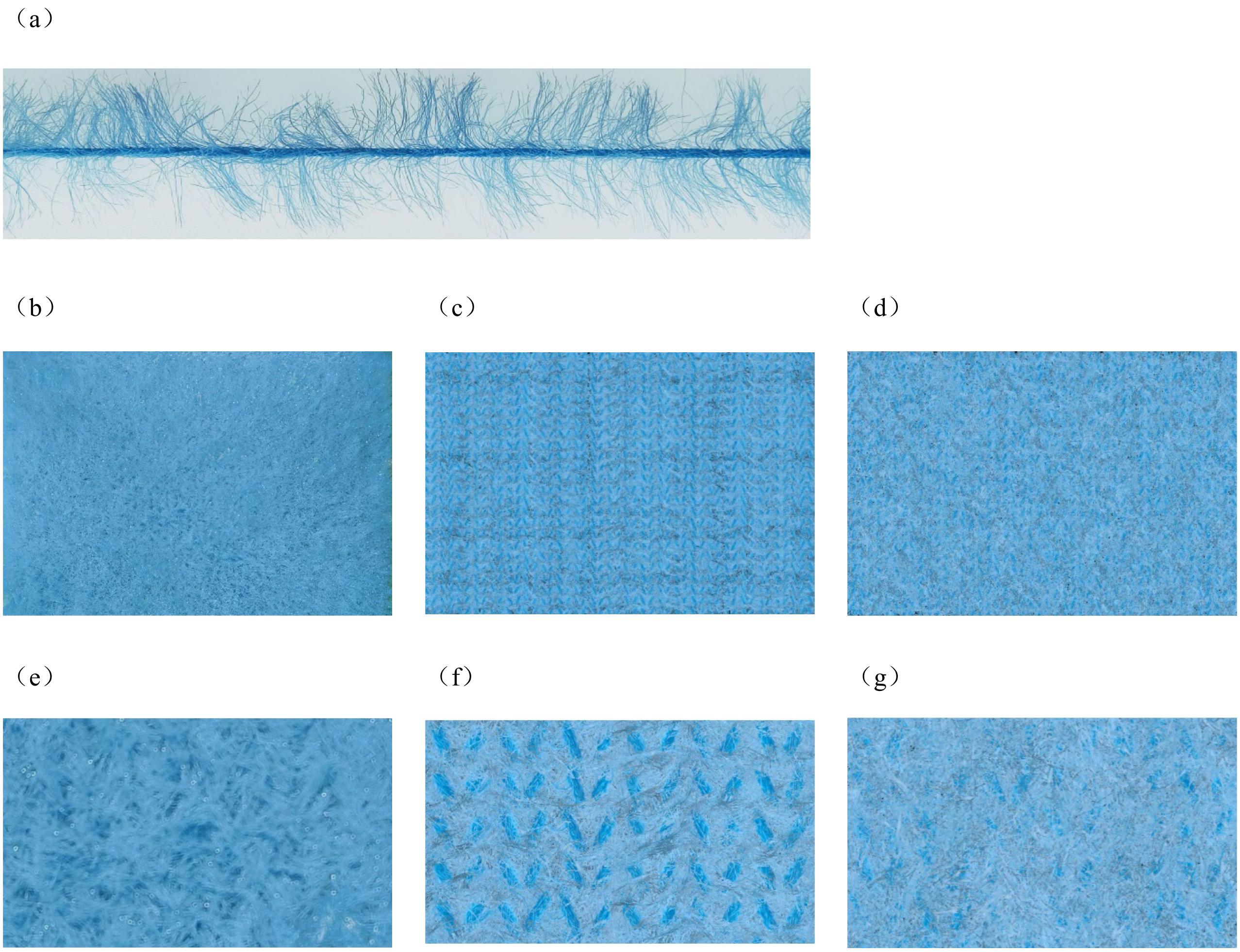

Fig. 10 Comparison of simulation effects between the smooth ribbon yarn model and the grooved ribbon yarn model for fuzz-rich yarn in weft-knit fabric organization. **a** Original yarn image, **b**, **e** Real fabric image and details, **c**, **f** Simulation results and details using the smooth ribbon yarn model, **d**, **g** Simulation effects and details of the improved ribbon yarn model

where the simulation results are closer to the actual fabric appearance.

In this study, we demonstrate the application of the grooved ribbon yarn model in simulating plain weft-knitted and cable-knit structures with different types of yarns, as shown in Fig. 11. The results highlight the diversity and adaptability of the model. From the figure, it can be clearly observed that different yarn types exhibit significant differences in the fabric structure. By incorporating various yarn types into the fabric, the interlacing and interactions between different yarns were simulated. The simulation results demonstrate that the proposed yarn model can efficiently and accurately simulate the knitted fabric structure composed of multiple yarns, further confirming the potential application of this method in the simulation of complex fabrics.

Moreover, the grooved ribbon yarn model significantly enhances the texture details and variations in simulated fabrics, making the simulation results not only visually closer to actual fabrics but also technically more precise, providing a powerful tool for textile design and manufacturing.

To further validate the performance of the proposed method, this study not only conducted simulations of single yarns but also extended the simulation to knitted fabrics composed of multiple yarns, as shown in Fig. 12. By incorporating various yarn types into the fabric, the interlacing and interactions between different yarns were simulated. The simulation results demonstrate that the proposed yarn model can efficiently and accurately simulate the knitted fabric structure composed of multiple yarns, further confirming the potential application of this method in the simulation of complex fabrics.

In terms of simulation speed, as shown in Table 1, our method demonstrates exceptional computational efficiency while maintaining high-quality simulation results. To address the simulation of large-sized fabrics, we have implemented specific optimizations. Specifically, when the

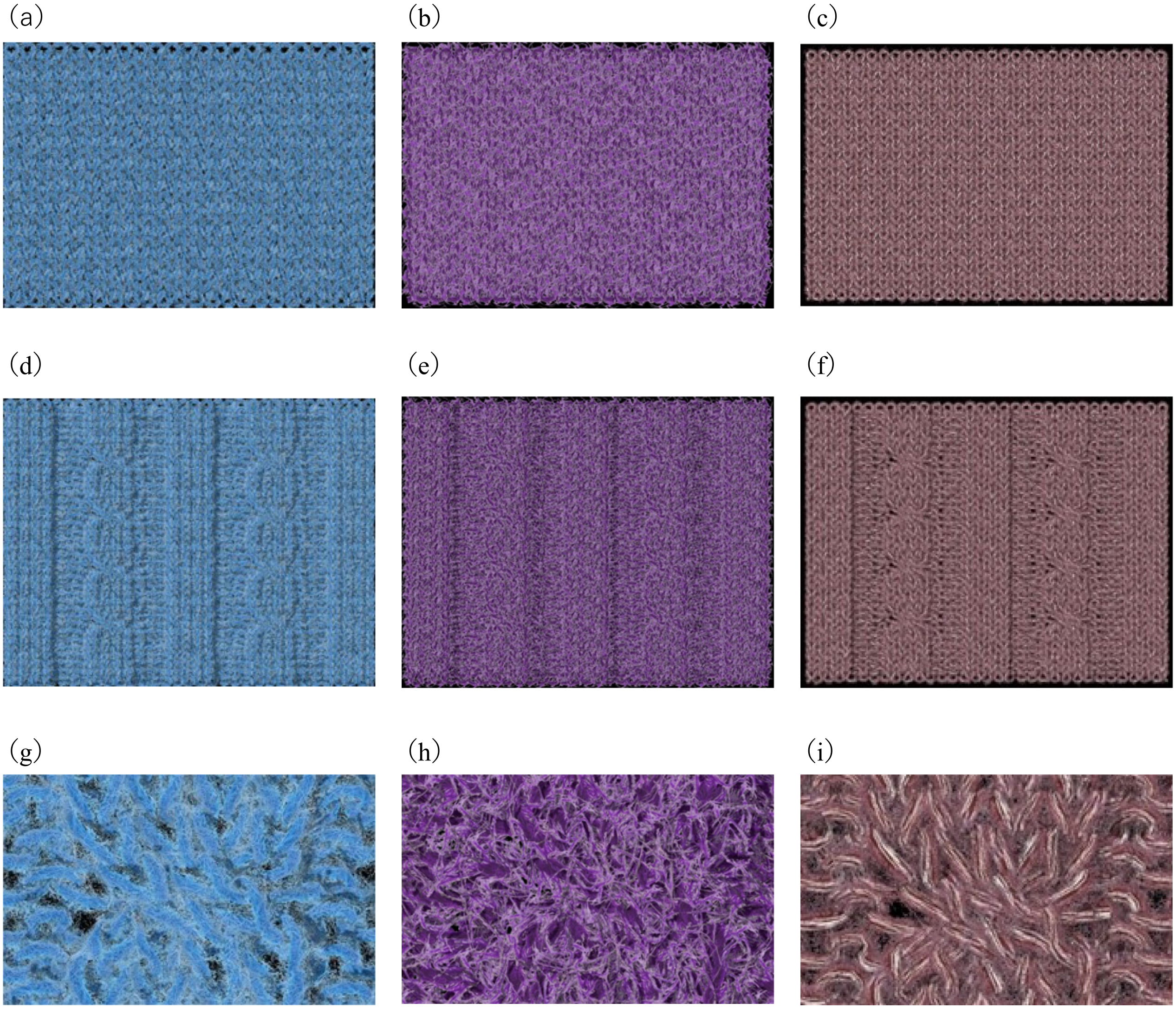

Fig. 11 Comparison of simulation effects of different types of yarns in different knit structures: **a**, **b**, **c** Simulation effect of different types of yarns in weft knitted plain fabric; **d**, **e**, **f** Simulation effects of different types of yarns in cable knit structure fabric; **g**, **h**, **i** Simulation detail of different types of yarns in cable knit structure fabric;

Fig. 12 Simulation results of multi-yarn knitted fabric

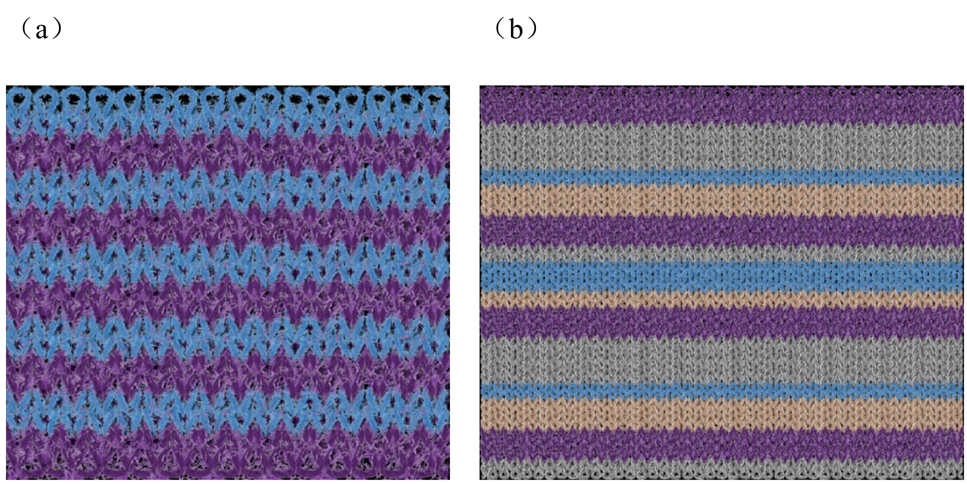

Table 1 Plain stitch modeling time

Fabric size	Control points	Yarn loop-by-loop modeling time (ms)	Replication modeling time (ms)
20*20	3220	163	163
50*50	20,050	733	185
100*100	80,100	3627	312

number of yarn loops in the simulation exceeds 500, we no longer generate each yarn loop individually but instead use the minimal-period replication method. This approach effectively reduces the computational load by periodically replicating portions of the fabric model, thereby significantly improving simulation speed. This optimization not only showcases the efficiency of the method but also ensures its feasibility for real-time fabric rendering and dynamic simulation.

The simulation speed is closely related to GPU performance, as our method utilizes GPU parallel computing to efficiently handle complex geometric and rendering calculations. In our experiments, the method achieved real-time performance on an NVIDIA A2000 GPU, a mid-range consumer-grade GPU with relatively modest computational power. This demonstrates the method's adaptability to less powerful GPUs, while higher-performance GPUs are expected to further enhance simulation speed and efficiency.

6 Conclusion

This research has successfully developed and validated a grooved ribbon yarn model that particularly enhances the interactive coverage function of fuzz, significantly improving the realism and detail representation of knitted fabric simulations. By achieving the natural coverage effects of fuzz in three-dimensional space, our model can more accurately capture and reproduce the complex interactions between yarns, thus closely matching the visual and physical properties of real knitted fabrics. Furthermore, by utilizing consumer-grade imaging equipment and physically based rendering methods, this study not only significantly improves the cost-effectiveness and operational convenience of the technology but also enhances the rendering realism of yarns and fibers by accurately simulating lighting and shadow effects. Our simulation technology maintains high-quality results while achieving instantaneous simulation speeds, showcasing its efficiency and potential in real-time rendering and dynamic simulation applications.

Acknowledgements This research was funded by the National Natural Science Foundation of China under the project titled "Research on the Automatic Generation of 3D Weaving Models for Fully Fashioned Knitted Garments Driven by Multiple Features," project number 62202068. We extend our gratitude to the National Natural Science Foundation of China for their support.

Funding National Natural Science Foundation of China, 62202068, Jiajia Peng.

Data Availability Data will be made available on request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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