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3D Pattern Construction and Its Application to Tight-fitting Garments for Comfortable Pressure Sensation

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Abstract: Tight-fitting clothing pattern reflecting the accurate information of the 3D body shape has been one of the challenges for garment industry, however, fitting problems still exist. The objectives of the paper is to develop a 2D pattern which fits tightly to the 3D human scan data for sports suits that need comfort and function for maximum performance. In this study, the user graphic interface application software for the semi-automatic garment pattern generation has been implemented using the triangle simplification scheme together with 2D projections of free-falling of 3D surface polygons keeping the original 3D surface area preservation. A typical application of the developed pattern to the functional body suits is presented and verification of the proposed method is also provided.

Keywords: 3D scan data, 2D pattern, Tight-fitting garment, Triangle simplification

Introduction

With the development of the 3D scanning technology, demand in tight-fitting pattern generation reflecting 3D curved human body is increasing. Although the development of tight-fitting clothing pattern from 3D human data has been a subject of interest, fitting problems still remain due to its multi-functional requirements in the system of textiles and human. Tight-fitting pattern generated directly from the 3D scan data could be used as a basic pattern for diverse clothing application for those in special needs. Tight-fitting pattern could be expanded for ordinary clothing or reduced for body contouring apparel using stretch fabrics. With some degree of inherent elongation in stretch fabric, we could construct ordinary garment for average person. However, any tension or folding on the surface of the clothing should be avoided as much as possible for those who need a record in racing or have special body form.

In order to deal with such tight-fitting problems, we first considered a semi-automatic generation for pattern development using computer simulations. In order for body scanning to support automated garment development efforts, it is imperative that we first be able to automatically integrate CAD systems which have the measurement system from 3D scanner, reconstruction algorithm of 3D surfaces from 3D scanned point clouds, and the efficient numerical algorithm for 2D flat development with minimum errors. The literatures for the pattern developments of 3D surfaces are numerous elsewhere [1-4]. From the set of point clouds, one can generate the faces using various methods. Some attempts have been made to provide software to generate 2D patterns for garments [4-7]. Hinds and McCartney [3,6] described flattening algorithm which operates on a polygon list of 3D triangles to provide 2D flattening. This algorithm is capable of handling the arbitrary sitting of stems which could involve darts or gussets depending on the nature of the curvature involved. Au and Yuen [5] generated the mannequin model used in the garment design. They used a non-contact three-dimensional whole body scanner to obtain the point cloud data of the body and fitted the data with predefined multiple Bezier surface patches to model a continuous body surface. Ramgulam [4] used the structured rectangular grids with finite number of elements to flatten 3D patches for 3D surfaces for applying fitting algorithm to any surfaces described numerically or analytically. Hinds *et al.* [3] developed patterns for simple surfaces in terms of Gaussian curvature. However, for the tight-fitting clothing, there has to be an intelligent examination of the tight-fitted garment to establish how critical the pattern flattening process should be in conforming to the original 3D surface. In this paper, we present a simple and accurate computational technique of quasi-automatic pattern algorithms for the tight-fitting clothing and their applications.

Unlike loose-fitting clothing, the three-dimensional surfaces of clothing on the human body consist of complex curved surfaces that are difficult to translate into 2D flat patterns without stretching and deforming for tight-fitting clothing. In the current study, in order to preserve the 3D topology of the tight-fitting clothing, we propose numerical algorithms to develop 3D surfaces which consist in many triangular meshes. First, we use the Delaunay triangulation method to have the three dimensional surface reconstruction triangulated meshes from the scanned data. From these triangular meshes, Garland's method [8] of triangle simplification is adopted, which could reduce the number of unstructured triangles without distorting the original shape with minimum errors. For the projection of reduced triangle patches on 3D surfaces to the arbitrary 2D plane without stretching and deforming, all triangular meshes on the 3D surface are divided into individual

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pieces with the scaling factor of 1/4. With this approach, every triangular mesh can be flattened into the 2D plane. This is the basic concept to develop the 3D surfaces. We use the free-falling techniques of the patches using the forth-order Runge-Kutta method to project the individual triangular meshes from the 3D surface in the 2D plane. The final 2D pattern can be obtained by the numerous ways for recombination of all triangular meshes projected on the 2D plane by the application software developed using graphics user interfaces and be refined by using the commercial software, for example, the Yuka CAD. The recombination of the individual triangular meshes depends on the designer's judgments and skills. In the current research, it is found that we have no troubles to get the final 2D pattern with high quality (see the section 3). It might be mentioned that, after finishing the 2D pattern, the size of this pattern should be recovered as the same area of the original surfaces of the three dimensional space by multiplying the scaling factor of 4.

Finally, clothing pressure is closely connected with the comfort and function of a garment. It is especially an essential factor for athletes' sports wear, women's foundation and burned patients' recovery shell. Therefore, it is important to understand key factors of the interaction between the human body and designed garment for the protective sports wear and finally to redesign the garments by optimizing the interactions with these key factors. One of them is the prediction of pressure between the garments and the human body. Zhang *et al.* [9] presented the mechanical model for numerical simulation of 3D dynamic garment pressure during wear using a finite element method. Adjusting pressure level in the construction of athlete's tight-fitting garments by reducing the elastic knit pattern is a challenging subject, which influence on the performance of the wearer directly. Therefore, in this study, relationships between the reduction rates of the basic pattern obtained from the 3D human scan and resultant clothing pressure were explored to improve the fit and pressure exerted by clothing using methods proposed by the current research.

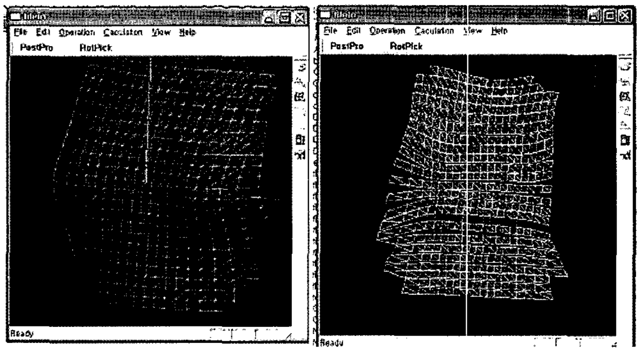
2D Pattern Development Procedures for Tight-fitting Clothing

To make two-dimensional patterns from 3D point clouds data for tight-fitting clothing on the human body, it is very important to define the geometries of patterns in compact, clear, and expandable way. The patterns made have the closed boundaries with dart that should keep the same area of the originally 3D tight-fit torso body, which would be difficult to get a perfect 2D pattern which has darts or gussets internally and externally because the garment patterns may have complex geometries. Unlike loose-fit clothing, the three-dimensional surfaces of clothing on the human body consist of complex curved surfaces that are difficult to translate into 2D flat patterns without stretching and deforming for tight-fitting clothing. It is impossible to get the 2D pattern without overlap from the arbitrary 3D meshes with keeping the original area of 3D surfaces. It means that not every finite triangular mesh on the 3D space can be projected on the 2D plane without deforming the mesh. In the current study, in order to preserve the 3D topology of the tight-fitting clothing, we propose simple numerical algorithms to develop 3D surfaces which consist in many triangular meshes.

We employed the simplification algorithm developed by Garland [8] into the application programs that adjusts the shape of the garment model with finite numbers of triangles. Finally, we developed a flat pattern generator which projected the garment into flat patterns conserving the same area of surface before and after projection. In this section we will discuss our numerical procedures to develop the 2D patterns for the tight-fitting clothing in details as follows.

Surface Construction and Simplification from the Laser Scan Data

A torso of a person is described by a point clouds obtained from the 3D laser scanning device. From the set of point clouds, one can generate the faces using various methods. Some attempts have been made to provide software to generate 2D patterns for garments [4-7]. However, for the tight-fitting clothing, there has to be an intelligent examination of the tight-fitted garment to establish how critical the pattern flattening process should be in conforming to the original 3D surface. There needs to be a full interior description of how the garment is mapped from 3D to 2D which will enable the reverse process to be achieved when draping is considered. In our research we employed the 2D pattern development with strips using the structured meshes as shown in Figure 1(a) for generation of the structured triangular meshes on the 3D surface and Figure 1(b) representing the corresponding 2D strips, which can be used to make the complete 2D patterns by using user graphics interface. The reconstructed triangular meshes were displayed on the graphic windows with various colors to visualize the iso-Gaussian curvature and quadric iso-surfaces. In addition, the 2D patterns



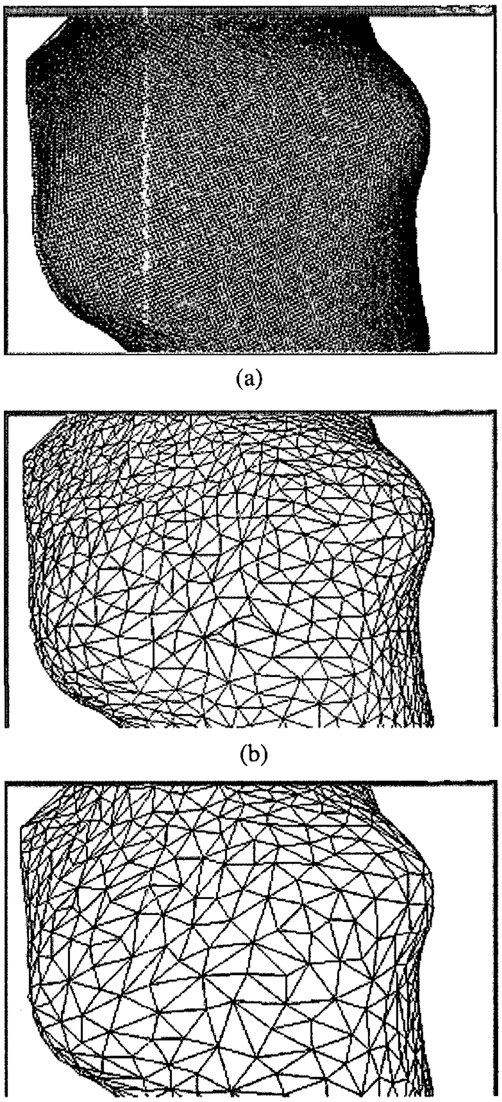
(a) (b)

Figure 1. Generation of (a) the structured triangular meshes on the 3D surface and (b) the corresponding 2D strips.

were obtained from the 3D structured striped mesh obtained from scanned point clouds by using the mouse motion such as dragging, picking, and moving on the screen window.

However, with this approach, one can lose the original 3D topology due to the reduction of point cloud data set regularly in the structured mesh generation, typically in the region of the high curvature. With this regard, in order to keep the topology in reduced elements, we use the simplification method in the unstructured meshes. The original unstructured triangular meshes can be obtained by using the standard triangulation schemes such as the Delaunay method. With these point cloud set, we obtain the generated triangular meshes using Delaunay triangulation method, which are shown in Figure 2(a).

Once the garment model that closely reflects the shape of the underlying body model has been generated, it should be projected into the 2D flat patterns for subsequent production. As shown in Figure 2(a) the number of triangular meshes from the original set of measured data is so large that simplification algorithms are needed to reduce the original unstructured meshes with minimum errors in topology. It might be mentioned that Garland in his thesis [8] proposed an efficient method to deal with this problems. He described a surface simplification algorithm which is capable of high reliability in producing simplification process. He used iterative pair contractions to simplify models and quadric error metrics with minimum errors in topology. We have employed its algorithm in our application software. The typical results for the sequence of simplifications generated using Garland's algorithm are shown in Figure 2(b) and (c). The original model has 12,045 unstructured triangular meshes and approximations in Figure 2(b) and (c) have 2000, 1000 faces, respectively. Figure 2(b) and (c) show a representative example of triangle simplification, and the overall shape of the breast is maintained. Original data contained approximately 12,045 triangles while its shape was maintained with about 5 % error margins when the amount of data was reduced into approximately 1000 triangles.


(a)

(b)

(c)

Figure 2. Unstructured triangular meshes generated by using (a) Delaunay triangulation method and (b), (c) application of the simplification method.

Simple Algorithms for Flattening 3D Triangular Meshes

Now we will discuss the flattening algorithm for the tight-fitting clothing. We present an algorithm to develop any triangulated meshes into the 2D plane with non-overlapping. The projected 2D triangles are connected the imaginary lines (called connected lines) with which one who is an expert designer in clothing manufacturing field can handle how to arrange and adjust all triangle pieces lied on the 2D plane with help of skillful judgment. Therefore, all triangular meshes flattened on 2D plane is adjusted and cut to make the final 2D patterns.

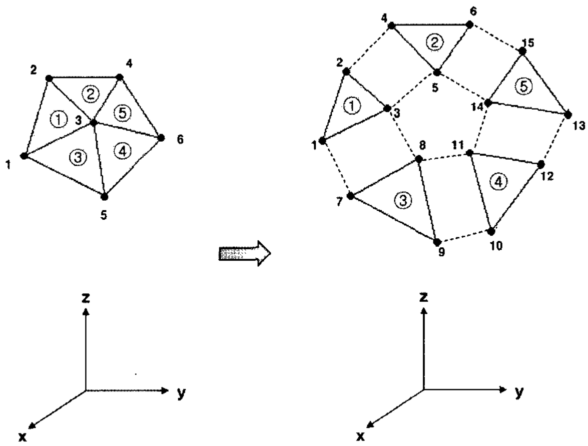


Figure 3. The sample five triangular meshes on the 3D surfaces (on the left) and divided into individual triangles with connected lines (on the right).

Let's consider five triangular meshes on the 3D surfaces as shown in Figure 3. These meshes are divided into five individual triangular meshes as shown in Figure 3 on the right, which have new connected lines generated. These new connected lines are used to arrange all triangular meshes unfolded on the 2D plane after projection of 3D triangular pieces. It might be mentioned that we can not have the divided meshes as shown in Figure 3 on the right without reducing the area of each triangle. In this research we reduce the area of all triangular meshes with the scaling factor of 1/4, which should be recovered the area into the original area of 3D surfaces.

These triangular meshes can be projected into the arbitrary 2D plane. We use the free-falling with gravity in order to project them using the fourth-order Runge-Kutta method. In that procedure, we use springs, dampers, and masses to simulate the free-falling of all triangular pieces by using particle based algorithm during time marching [10]. The triangular meshes are considered as the rigid body and the connected lines have the arbitrary values for material properties so that these lines are contracted or elongated depending on the system of the initial meshes during the free-falling.

From this approach we can have the projected triangular meshes on the 2D plane, for example, in the x-y plane as shown in Figure 4. It should be mentioned that the projected area is scaled down, for example, the half of the original area of the triangular mesh as shown in Figure 4.

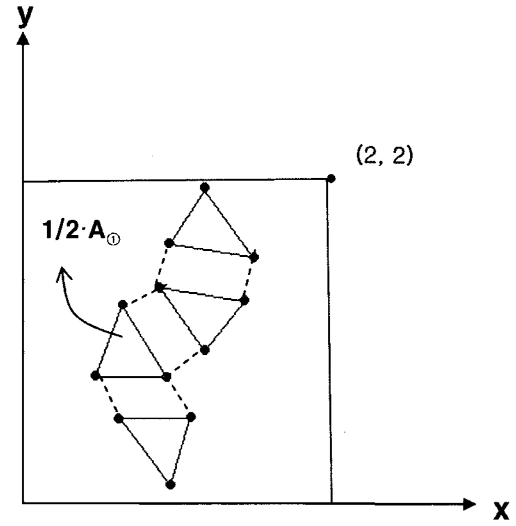


Figure 4. The projected triangular meshes on the 2D plane.

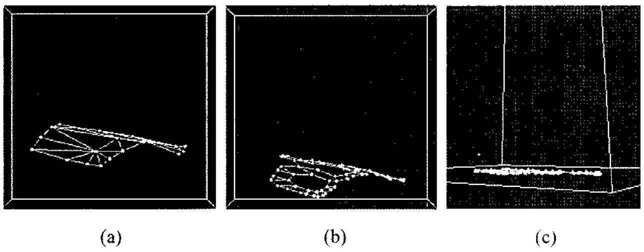

(a) (b) (c)

Figure 5. Free-falling process: (a) before free falling of divided triangular pieces, (b), (c) falling of 1/4 reduced triangular pieces with connection lines.

Figure 5(a) shows the image before the free falling of the triangular meshes and Figure 5(b) the intermediate stage of the free falling which shows the 1/4 reduced triangular pieces with connection lines to retain the interrelated information of connection of the triangular pieces. Figure 5(c) shows the final stage of the fallen triangular pieces which lies on the 2D plane.

Figure 6(a) shows the retrieved free-fallen triangular pieces with connection lines as it is, and the connection lines between triangular pieces serve as guidelines for the recombination of the triangular pieces. Figure 6(b) shows the triangular pieces without connection lines. When one remove these lines one can not recombine these triangular pieces in to the final 2D patterns since there is no information to sum up them. That is why these guide lines are introduced in the current research.

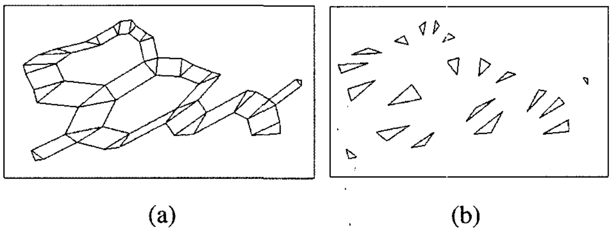
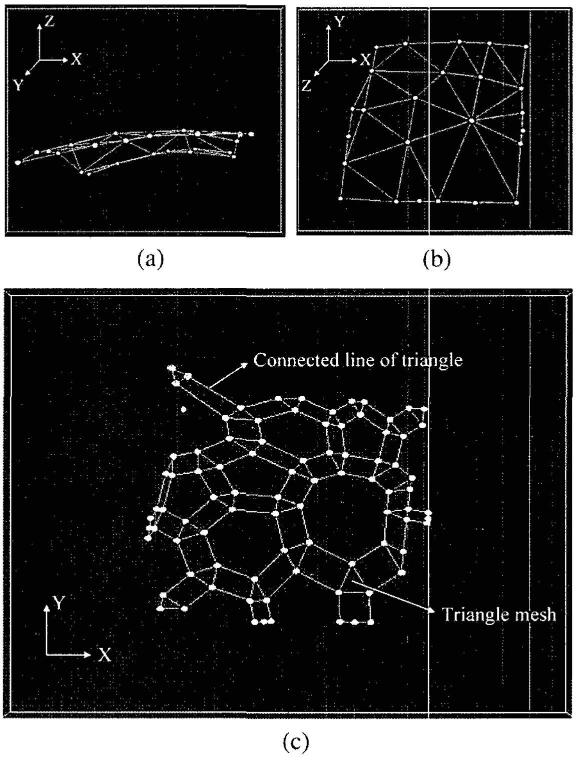

(a) (b)

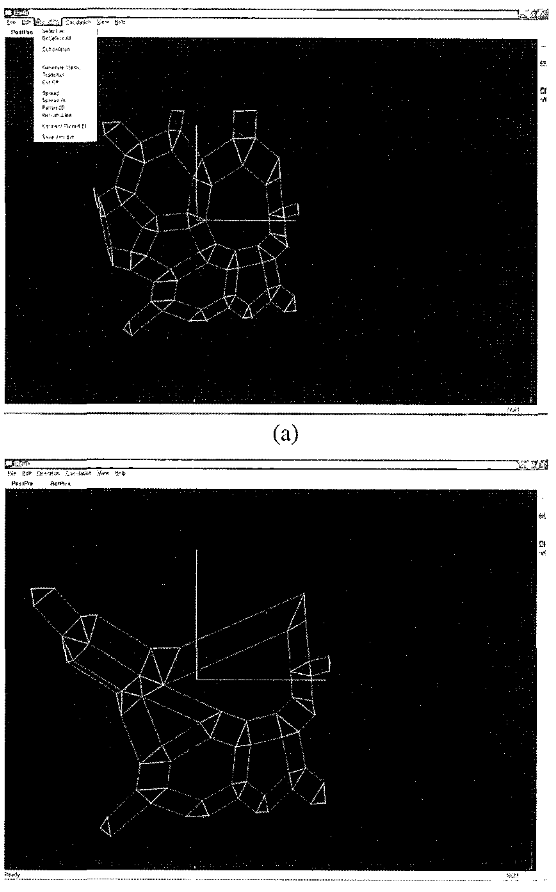
Figure 6. The retrieved free-fallen triangular pieces (a) with connection lines and (b) without connection lines.



(a) (b)

(c)

Figure 7. Typical numerical example by using the proposed method.



(a)

(b)

Figure 8. The final 2D pattern in this example can be obtained by (a) recombination of all triangular meshes by the application software and (b) arrangement by the graphic user interfaces.

Typical Numerical Example Using the Proposed Method

Figure 7(a) and (b) show original generated meshes and (c) the mapping of the triangular meshes from 3D to 2D plane. As shown in Figure 7(c) one can have the final triangular pieces with loss of errors.

The final 2D pattern in this example can be obtained by recombination of all triangular meshes by the application software developed using graphic user interface as shown in Figure 8(a). In this platform triangles can be selected and moved to combine them. Some triangles selected by mouse picking can be automatically connected as shown in Figure 8(b). In the current research, global arrangements are done using this application software and refined arrangements are continued using commercial software, the Yuka CAD.

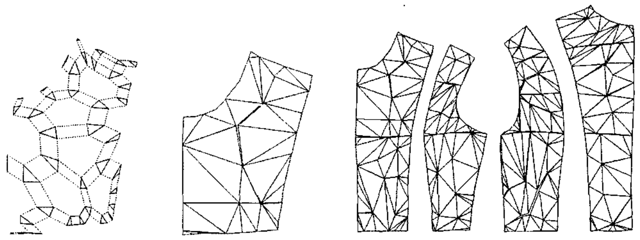


Figure 9. Obtaining 2D triangular patches and a merged block using the proposed method.

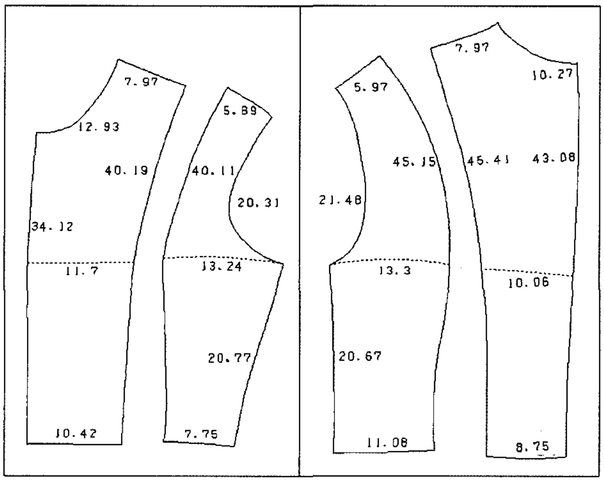


Figure 10. Men's basic pattern using the proposed methods in this study (Actual length of pattern line was indicated in the figure).

Table 1. Surface area between the original 3D men's upper manikin and 2D pattern directly developed from 3D data

	Front (middle)	Front (side)	Back (side)	Back (middle)
3D manikin, upper (cm^2)	463.02	322.39	423.24	506.37
2D pattern (cm^2)	465.23	320.83	423.84	504.72
Difference (cm^2, %)	+2.21 (0.4)	−1.56 (−0.4)	+0.6 (0.1)	−1.65 (−0.3)

Applications to the Tight-fitting Clothing for Comfortable Cycle Wear

Basic Pattern Generation from the Laser Scan Data

The 3D scan data of a male manikin was obtained using Exyma-E1200 (Z-SCAN Co., Ltd., Korea) and segmented into several parts using RapidForm 2004. Triangle simplification was used to reduce the 3D scan data points, while maintaining the original 3D shape. The Runge-Kutta method was applied to mapping the segmented triangular patches from 3D space in a 2D plane. As a next step, each triangular patch was connected to the next one by merging its vertexes together in a block (Figure 9). Each block was again connected to its nearby block to make a basic pattern as shown in Figure 10. Total surface area between 3D manikin and the 2D pattern developed was compared in Table 1, and length of major parts between 3D manikin model and 2D were compared each other (Table 2). Difference in surface area was below 1 %, and length was 1.2 % at most [11].

Table 2. Length difference between 3D manikin and 2D pattern

	3D (cm)	2D pattern		
		Length (cm)	Difference (cm)	(% difference)
Center line, front	34.35	34.12	−0.23	−0.60
Center line, back	43.35	43.08	−0.27	−0.60
Princess line, front	40.42	40.19	−0.23	−0.50
Princess line, back	45.50	45.41	−0.09	−0.19
Neck line, front	13.10	12.93	−0.17	−1.20
Neck line, back	10.39	10.27	−0.12	−1.10
Arm scy, front	20.26	20.31	+0.05	+0.20
Arm scy, back	21.47	21.48	+0.01	+0.04
Chest line, front	25.16	24.94	−0.22	−0.80
Chest line, back	23.58	23.36	−0.22	−0.90
Waist line, front	18.29	18.17	−0.12	−0.60
Waist line, back	20.01	19.83	−0.18	−0.80
Shoulder line	13.94	13.86	−0.08	−0.50

Cycle Wear Development Using Stretch Fabric

A basic pattern was obtained by scanning a human subject using whole body scanner Model WB4 (Cyberware, Inc., USA, Figure 11). Using the processes mentioned, a 2D basic pattern could be created from the 3D human scan data without considerable correction on the pattern. Outline of the pattern was slightly trimmed to get the natural curve by the Yuka pattern-making program (Figure 12).

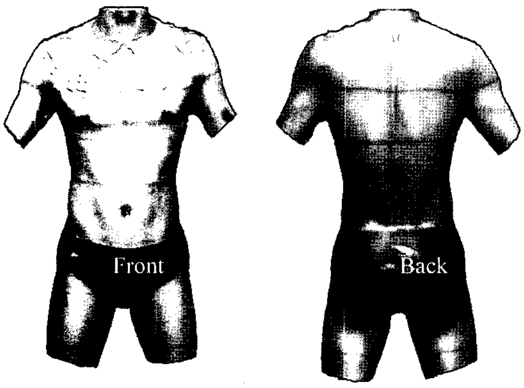


Figure 11. Acquired 3D human data using Cyberware.

The basic pattern was divided into four parts and changed into reduced patterns according to the amount of the fabric stretch followed by ASTM D2594. The wale and course stretch percentages of the experimental fabric (91.4 % polyester and 8.6 % polyurethane) were 16 % and 20.5 %. To find the appropriate reduction rate, the basic pattern from the 3D scan data was reduced by five types, namely the O-pattern (0 % reduction rate, original basic pattern), modified Z-pattern as suggested by Ziegert [12], 3T-pattern (the two-thirds of the amount of reduction suggested by Ziegert), T-pattern (the total amount of the fabric stretch), and A-pattern (15 % reduction in all directions). Table 3 shows the reduction rate and grading value of wale and course for the five experimental garments.

Subjective wear sensations of the experimental garments were rated using the seven Likert scale for 5 consecutive days. While wearing the garments, a subject was told to have five various postures including waist flexion and sitting etc. Likert type scale was used for the evaluation, where 7 point indicates that it gives the best fit as a cycle wear. Clothing pressure was also measured using the air-pack type pressure sensor (model no. AMI 3037-2) at six locations, left chest, left shoulder, left abdomen, left thigh, scapula, and pelvis.

Clothing Pressure of the Five Experimental Cycle Wear

Figure 13 shows the experimental garment worn on the plaster figure. The pressure distribution of both 3T-pattern and Z-pattern were 2~4 gf/cm^2, and that of the T-pattern was 5~11 gf/cm^2 (Figure 14). The pressure range of the A-pattern which is one of the widely used short cut reduced pattern was about 0~8 gf/cm^2. In case of the basic pattern developed directly from 3D scan data without any reduction rate, pressure distribution was very even within the range of

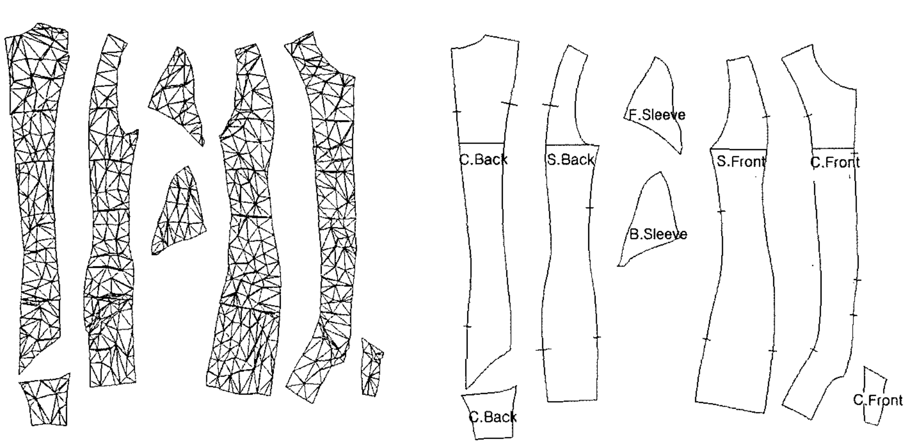


Figure 12. 2D pattern development by attaching each of the blocks and resultant basic patterns.

Table 3. The five reduction rates and grading values

	O-pattern	Z-pattern	3T-pattern	T-pattern	A-pattern
Length (N.P. ~ Crotch), (cm) (reduction rates, %)	85.75 (0 %)	80.35 (7 %)	78.55 (9 %)	74.94 (13 %)	72.89 (15 %)
Chest width, (cm) (reduction rates, %)	23.31 (0 %)	21.28 (9 %)	20.58 (12 %)	19.21 (18 %)	19.81 (15 %)
Grading value, wale (cm)	0	5.34	7.13	10.69	12.85
Grading value, course (cm)	0	2.38	3.18	4.77	3.5
Total Area of pattern (cm^2) (reduction rates, %)	3918 (100 %)	3313 (16 %)	3114 (21 %)	2731 (31 %)	2830 (28 %)

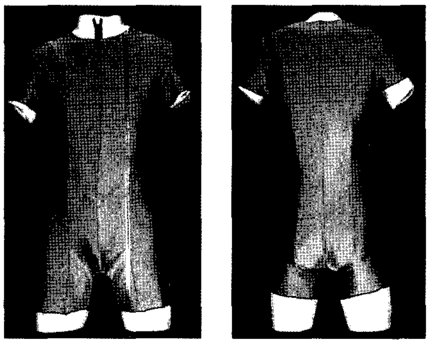


Figure 13. Experimental garments worn on the plaster figure.

Figure 14. Clothing pressure of experimental garments at six locations on the body.

between 0 and 1 gf/cm^2.

Among the five garments, the 3T-pattern was superior in terms of subjective sensation and fit. The average wear sensation values of 3T, A and Z-patterns were 5.69, 5.34, and 5.31, which was significantly different ($p<0.001$) from other garments. The most sensitive part responding the pressure exerted by the garments was the front rise, where extra ease for good fit and sensation has to be considered.

As days of wearing progressed from the first trial on the first day to the fifth trial on the firth day, the subjective ratings were changed; after each trial, subjects preferred more tight-fitting garment. Therefore, it is noted that time variable or experience of wear trials should be considered when the subjective pressure sensation of the tight-fitting garment is evaluated.

Conclusions

The goal of this research was to create a 2D tight-fitting pattern with the proper pressure from the 3D human scan data considering the fabric stretch. In this research, we have proposed the simple flattening method incorporated with the graphic user interface application programs. We have discussed the flattening algorithm for the tight-fitting clothing with keeping the original area of 3D surfaces with minimum errors. We have presented the simple algorithm to develop any triangulated meshes into the 2D plane with non-overlapping. The projected 2D triangles are connected the imaginary lines(called connected lines) with which one who is an expert designer in clothing manufacturing field can handle how to arrange and adjust all triangular pieces lied on the 2D plane with help of skillful judgment. Therefore, all triangular meshes flattened on 2D plane is adjusted and cut to make the final 2D patterns. In the current research, global arrangements are done using the user graphic interfaces in this application software and refined arrangements are continued using commercial software, the Yuka CAD.

As a result for its application to the tight-fitting clothing for comfortable pressure sensation we have also demonstrated their applications for the clothing pressure using some typical 2D patterns examples obtained by our proposed methods. Among the five garments, the 3T-pattern was superior in terms of subjective sensation and fit. The pressure of the 3T pattern was 2~4 gf/cm^2 at five locations on the body, which is almost the same or a bit higher than that of Z-pattern (Ziegert pattern [12]). In case of tight-fitting overall garment, the reduction rates of the pattern in the wale direction is more critical to the subjective sensation than the course direction. It is recommended that the reduction grading rules of course direction should be larger than that of Ziegert for a better fit of tight-fitting garments. In case of wale direction, however, reduction grading rule should be kept the same as suggested by Ziegert.

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