Surface Shape Features of 3D Tight-Fitting Skirts
Using Angle Curvatures in Virtual Reality

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Abstract

This study examined the significant factors involved in a custom-made garment creation system used for 3D fitting and 2D patterns for skirts. 3D tight-fitting skirts were developed from 3D imaginary skirt forms simulated by constructing individual 3D body shapes using a convex hull. The features of the 3D curved tight-fitting skirt surface shapes of 1,044 females were extracted by means of the angle curvatures of the triangle mesh 3D skirt shapes to yield information that can support communication between retailers and their consumers. There are deficit angles of concentrated Gaussian curvature $K_c$ on interior area vertexes and concentrated geodesic curvature $k_c$ on the exterior boundary waistline and hemline vertexes. We identified the features of the 3D tight-fitting skirt curved surface shape, including the presence of darts, for a considerable number of female for 2D pattern generation, regardless of the body size and without using cloth or having to sew a skirt. We then classified the 3D tight-fitting skirt curved surface shapes based on the features of the areas, including the female ages. A viable virtual reality custom-made tight-fitting skirt creation system was established to support the development of an eco-clothing lifestyle and to provide the information needed for the project to succeed.

Key Words: Custom-made garment creation system, 3D imaginary shapes, Concentrated Gaussian curvature, Concentrated geodesic curvature, Classification of 3D tight-fitting skirt curved shapes

1. Introduction

In the future, we will order garments created to fit our individual 3D body shapes via the Internet. If the requisite garment ordering, purchase, and sale system is useful and rational, this process will achieve lower levels of waste for both the producers and consumers. This approach to making and selling garments could be considered one way of pursuing an “eco-clothing lifestyle.” Therefore, we have proposed the construction of a 3D fashion factory or boutique ordering system (denoted by 3D-FFB) to support communication between the retailers and consumers utilizing the 3D body shapes and the 3D garment design images for adult women’s garments as an implementation of the eco design using IT reported in previous papers [1–12]. Previous research studies examined the 3D body shapes and 2D garment patterns of females and males via the 3D and 2D curved surface curvature using angles [13–20].

In this study, we developed a custom-made tight-fitting skirt creation system in virtual reality for an ecologically friendly design that requires neither the use of cloth or sew skirts. The features of the 3D curved tight-fitting skirt shapes on the 3D body shape of 1,044 females were extracted using a virtual reality custom-made system for 3D skirts. Our objective is to provide images and curvatures of 3D tight-fitting skirt shapes that are capable of helping people to understand the elusive nature of fitting skirt shapes in a custom-made system and to show them how to extract the features of 3D tight-fitting skirt curved shapes. We also aim to provide the information that will support communication between retailers and consumers about production and selection details.

Many garment and cloth simulation studies [21–28] have been developed. Previous studies include limited shapes or wrinkles of a garment [21, 22]; the development of a virtual draping system [23]; a method for making clothing patterns [24, 25]; the production of clothing shapes by deforming the wireframe model using body features [26]; a clothing pattern made by using the planes and boundaries of a garment [27]; and the method of creating 3D garment shapes by attaching the garment pattern on the body model and sewing it [28]. There are few research studies about the development of a garment making system that includes fitting the real body shapes of a great many people. We studied the extracted features of 3D tight-fitting skirt curved shapes, developed from
a large number of 3D body shapes, using the results of 3D tightfitting simulations which were designed to facilitate ordering garments created to fit individual 3D body shapes.

We used the deficit angles of triangle meshed vertices to measure the 3D tight-fitting skirt curved shapes. The angles of concentrated Gaussian curvature $K_c$ on the interior skirt surface and concentrated geodesic curvature $k_c$ on the exterior boundary skirt line were investigated to determine the 3D shapes and 2D curved lines for a great many females regardless of their body size. In accordance with the Gauss-Bonnet theorem [29], the total angle values of “zero” of Sum $K_c$ and Sum $k_c$ are found in all the 3D and 2D skirts. The differences in the 3D skirt shapes can be extracted by the distribution of the $K_c$ and $k_c$ angle values on the 3D skirt surface area. A new method for determining the 3D body, bodice, and garment shapes on the common stages of angles with curvatures is presented. In this study, we are able to realize the classification for extracting the 3D curved skirt shape types based on the 3D body shape, including 2D pattern generation and the ages of 1,044 females; this information will be used to support communication between retailers and consumers. Furthermore, new measurements for the 3D garment curved shape using the $K_c$ and $k_c$ angle values are suggested to correct the insufficiency of the length measurement using a tape measure.

2. Experimental method and theoretical background

2.1 Automatic 3D garment made-to-order-system via computer simulation and creation of 3D tight-fitting skirts for females

The 3D body measurement system and the virtual 3D skirt and bodice system are shown in Fig. 1. The 3D body shapes of females were measured for 10 seconds using a non-tactile 3D body measuring instrument (Body Line Scanner C9036-02, Hamamatsu Photonics Co., Ltd.). The system of measurement was a scan method from the upper to the lower human body using four sensor heads with a laser diode light source and a CCD camera (see Fig. 1 - ①). The 3D body shape was produced as a high-density polygon (the wireframe model with 180 vertexes at intervals of 2.5 mm on a body surface).

During the first stage, a dress form for covering a 3D body surface was arranged by means of a convex hull extraction of the wireframe model with concave and convex vertexes from the crotch height to the neck height at 2 mm intervals except for the arms (see Fig. 1 - ①). Each covering plane was formed using these convex vertexes on the wireframe lines. During the second stage, laminated convex wireframe shapes were used to form a 3D skirt from the waist height to knee height (hemline of the skirt). The desired skirt that covered a personal 3D body shape was constructed as a 3D article upon simulation. The 3D skirt from the hip line to the hemline was formed using the same wireframe of the hip line like an elliptic cylinder. The real 2D pattern was developed using the 3D skirt surface and then pieces of cutting 2D cloth together were sewed (see Fig. 1 - ②).

2.2 3D tight-fitting skirt curved shape measurement

The subjects of 1,044 females selected by a random sampling from a wide age range (18 to 84 years old). The means and SD (standard deviations) of the female ages and their body measurements are shown in Table 1. The mean values of these body measurement items were not significantly different (significance level 5%) from the mean values provided by HQL [30].

The 3D skirts for our system were measured using 300 setting vertexes (X, Y, Z) on nine vertical wireframe lines from the waistline to the hemline. Their measurement wireframe lines were equally divided into 3 height sections from the waistline to the hip line, and the height was equally divided into four sections from...
the crotch line to the hemline. The detailed measurement points of 300 setting vertexes are shown in Fig. 1 - ①. The 3D skirts were divided into 540 triangle meshes (faces) with a total of 300 vertexes (Fig. 2). The concentrated vertex angles of the 540 triangle faces were computed to extract the 3D skirt curved shapes. This angle measuring method for a triangle-shaped mesh surface is suited to 2D pattern development and the analysis of a 3D tight-fitting skirt curved shape.

2.3 Theory and analysis

Fig. 2 illustrates the theory for our 3D skirt shape using 540 triangle meshes (faces), 300 vertexes, and 840 edges. The Euler number is zero according to the values of the faces, vertexes, and edges (300 – 840 + 540 = 0). The concentrated vertex angle of every triangle produced the deficit angles of $K_c$ (by $K_c = 360^\circ(2\pi - \theta_n)$) on the interior area vertexes and $k_c$ (by $k_c = 180^\circ(\pi - \theta_n)$) on the exterior boundary waistline and hemline vertexes. The definition of the angle values is as follows: $K_c > 0$; elliptical curved shape, $K_c < 0$; hyperbolic curved shape, $K_c = 0$; developable surface curved shape without darts on the 2D pattern, $k_c > 0$; convex line curved shape, $k_c < 0$; concave line curved shape, and $k_c = 0$; straight line curved shape. The $K_c$ values show the waist and hem lines’ curved shapes of the 2D pattern. The total angle values of “zero” for the Sum $K_c$ and Sum $k_c$ in all the skirts were determined by using the same method used in the Gauss-Bonnet theorem (Fig. 2). The 3D skirt curved shape on each female was examined via a principal component analysis (PCA) and a cluster analysis of the $K_c$ and $k_c$ values.

3. Results and Discussion

3.1 Theory of 3D curved tight-fitting skirt surface shapes

The total angle values of “zero” of the Sum $K_c$ and Sum $k_c$ in all the skirts can be determined according to the Gauss-Bonnet theorem in Fig. 3. The distribution differences between the Sum $K_c$ and Sum $k_c$ values denoted the features of each 3D skirt’s curved shape. The Sum $K_c$ and Sum $k_c$ mean values of the 3D skirt show the same positive and negative value, $+80.18^\circ$ (SD = 17.16) and $-80.18^\circ$ (SD = 17.16) in this study. A comparison is then performed using these values of the 3D skirt and the other body areas from previous papers [13–20]. The

![Fig. 3](image-url) The total angle values of “zero” of Sum $K_c$ and Sum $k_c$ in all the skirts. The distributions between the Sum $K_c$ and Sum $k_c$ values in each female are able to represent the differences in the 3D tight-fitting curved shapes.
3D trunk surface and 2D tight-fitting bodice pattern displayed the same total values of “-720°” of the Sum $Kc$ and Sum $kc$ in all the females of previous papers. Each total value of the 3D trunk surface was divided by the mean values of Sum $Kc$ -108.86° and Sum $kc$ -611.34°. Each total value of the 2D tight-fitting bodice pattern had the mean values of Sum $Kc$ -96.25° and Sum $kc$ -623.75°. The Sum $Kc$ and Sum $kc$ represented approximately the same mean values for the same trunk body surface and pattern in both the 3D and 2D cases. Using differential geometry and differential topology, the Euler number for the trunk was determined to be 2. Therefore, based on the Gauss-Bonnet theorem, the total values of the Sum $Kc$ and Sum $kc$ for all the female trunks were “-720° = Euler number $2 \times -2\pi (-360°)”. The differences between the 3D body trunks with convex and concave surfaces and the 2D tight-fitting bodice patterns covering a convex surface were confirmed in previous papers [13–20].

On the other hand, the mean values of the Sum $Kc$ and Sum $kc$ of the tight skirt area in this study were lower than those of the two trunk areas in previous papers. Compared with the two trunk areas, the tight skirt area represents the lower curved surface shape.

### 3.2 Features of 3D curved tight-fitting skirt surface shapes in mean values

Table 2 shows the mean values of the distribution angles of the Sum $Kc$ and Sum $kc$ in each area and the divided positive $+Kc$ or $+kc$ and negative $-Kc$ or $-kc$. The $+Kc$ value represents the elliptical curved shape, while the $-Kc$ value represents a hyperbolic curved shape in Fig. 2. The $+kc$ value represents the convex boundary waistline shape, while the $-kc$ value denotes the concave boundary waistline shape, in this study. For the values when the $+Kc$ and $-Kc$

![Fig. 4 Vertex areas of the 3D tight-fitting skirt for extracting the different distribution features of the $Kc$ and $kc$ values.](image)

are near 0, the skirt surface includes the 2D skirt pattern without the darts. For the values close to 0 of $+kc$ and $-kc$ value, the result is a nearly straight boundary waistline.

Therefore, the highly elliptical curved shape and concave boundary waistline of the left and right side areas in Fig. 4 were determined from the high Sum $+Kc$ (LS: $+Kc$ and RS: $+Kc$) and Sum $-Kc$ (LS: $-Kc$ and RS: $-Kc$) mean values in Table 2. Next, the mean value of Sum $+Kc$ on the center back area (CB: $+Kc$) was higher than that of the center front area (CF: $+Kc$).

The mean values of Sum $-Kc$ and Sum $+kc$ in all the areas were nearly 0 values. The interior areas of all the 3D skirt shapes nearly constructed the bodices of the convex ($+Kc$) curved surface for a garment by using a computer. The hemline shapes of all the 3D skirts are straight lines with zero $kc$ values. However, the 3D skirt shapes of all females shapes may reflect the majority of the $-Kc$ and $+kc$ values in all the areas.

The 3D skirt curved shapes can be extracted in detail using the angle values of $Kc$ and $kc$. It will be useful for the garment design process to use the $Kc$ and $kc$ angle values with the length values of the body and garment measurements.

### 3.3 Extraction of principal components for 3D tight-fitting skirt curved shape

Table 3 shows the factor loading of the evaluation value of the 3D skirt curved shape in each area from the PCA according to the mutual correlation coefficients. The six principal components (PC1 to PC6) with the 3D skirt curved shape eigenvalues of 1.00 or more are presented and comprised 77.591% of the cumulative contribution ratio. The scores for PC1 to PC6 are abbreviated as PCS1 to PCS6. Each area curvatures show the LS+$Kc$ to CF+$Kc$, LS-$Kc$ to CF-$Kc$, LS+$kc$ to CF+$kc$, and LS-$kc$ to CF-$kc$.

PC1 had slightly higher or high positive values (0.533 to 0.733) of the $+Kc$ and $-Kc$ in all the interior areas except for the negative value (-0.538) of CB-$Kc$. Furthermore, PC1 included slightly higher or high negative values (-0.589 to -0.798) of all the LS-$Kc$ to CF-$kc$ and slightly high negative value (-0.539) of the CF+$kc$. The features of the 3D skirt curved shape from the majority of the areas were extracted. Although the higher positive or negative PC1 values are represented by all the LS-$Kc$ to CF-$Kc$ and CF+$kc$. Each difference

| Areas          | $Kc$ or $Kc$ | mean | SD  |
|----------------|-------------|------|-----|
| Left side (LS) | $+Kc$       | 7.14 | 0.21|
| Left side (LS) | $-Kc$       | -1.43| 0.21|
| Left side (LS) | $+Kc$       | 29.39| 0.07|
| Left side (LS) | $-Kc$       | -2.86| 0.14|
| Right side (RS)| $+Kc$       | 12.64| 0.84|
| Right side (RS)| $-Kc$       | -2.92| 2.20|
| Center back (CB)| $+Kc$     | 0.06 | 0.24|
| Center back (CB)| $-Kc$     | -13.60| 4.54|
| Center back (CB)| $+Kc$     | 21.56| 8.34|
| Center back (CB)| $-Kc$     | -2.55| 2.39|
| Center front (CF)| $+Kc$    | 10.22| 7.83|
| Center front (CF)| $-Kc$    | -1.75| 1.37|

+ $Kc$: positive $Kc$ value denoting the elliptical curved shape; 
$-Kc$: negative $Kc$ value denoting the hyperbolic curved shape; 
+ $kc$: positive $kc$ value denoting the convex geodesic line shape; 
- $kc$: negative $kc$ value denoting the concave geodesic line shape. 
Number of 3D tight-fitting skirts = 1,044. Fig. 4 shows each area of $Kc$ and $kc$. The data is rounded off to the third decimal place.
Table 3  Factor loadings of positive and negative Kc or kc based on areas.

| Areas               | Kc   | PC1   | PC2   | PC3   | PC4   | PC5   | PC6   |
|---------------------|------|-------|-------|-------|-------|-------|-------|
| Left side (LS)      | +kc  | -0.101| 0.094 | 0.052 | 0.414 | 0.091 | 0.420 |
| Left side (LS)      | -kc  | -0.539| 0.644 | 0.440 | 0.301 | -0.121| -0.325|
| Left side (LS)      | +kc  | 0.654 | -0.026| 0.456 | -0.035| -0.077| -0.284|
| Right side (RS)     | +kc  | -0.100| 0.292 | -0.303| 0.493 | 0.045 | 0.030|
| Right side (RS)     | -kc  | 0.623 | 0.517 | 0.117 | -0.401| 0.014 | 0.557|
| Right side (RS)     | +kc  | 0.577 | -0.412| -0.264| 0.573 | -0.150| -0.460|
| Right side (RS)     | -kc  | 0.785 | -0.027| 0.426 | -0.058| 0.344 | 0.075|
| Center back (CB)    | +kc  | 0.098 | 0.349 | -0.322| 0.467 | 0.198 | 0.330|
| Center back (CB)    | -kc  | 0.113 | 0.847 | -0.170| -0.099| 0.194 | -0.114|
| Center back (CB)    | +kc  | 0.533 | -0.784| 0.041 | 0.156 | 0.021 | 0.136|
| Center back (CB)    | -kc  | 0.733 | -0.007| 0.272 | -0.092| 0.244 | -0.040|
| Center back (CF)    | +kc  | -0.539| 0.012 | -0.271| -0.121| 0.528 | -0.257|
| Center back (CF)    | -kc  | 0.798 | -0.386| 0.132 | 0.001 | 0.114 | 0.046|
| Center back (CF)    | +kc  | 0.728 | 0.461 | 0.143 | -0.040| -0.063| -0.078|
| Center back (CF)    | -kc  | 0.447 | 0.126 | 0.310 | 0.309 | -0.440| 0.344|

Eigenvalues          | 4.791| 2.557 | 1.962 | 1.308 | 1.150 | 1.047 |
Contribution ratios  | 29.942| 15.984| 9.761 | 8.173 | 7.186 | 6.545 |
Cumulative contribution ratios (%) | 29.942| 45.926| 55.686| 63.860| 71.046| 77.591|

Underlined values and values in white boxes show factor loading of approximately ±0.5 (rounded off to one decimal place) or more.

in the high and low –Kc or +kc values in these areas is minimal. The reasons for the small difference in the values for the –Kc and +Kc lies in those areas of approximately 0 of the mean and SD values are shown in Table 2. The eigenvalue is 4.791 and accounts for 29.942% of the contribution ratio. The higher PCS1 is mainly due to the high concave boundary waistline shape of the CF areas, and the low elliptical curved shape of the CB area, and vice versa for the lower PCS1. PC1 represents mainly the 3D curved shapes of the CF areas, and the low elliptical curved shape of the CB area, and the elliptical curved shape are extracted by PCS2. PC2 seems to be the factor responsible for the 3D skirt curved shape of the CB area.

PC3 included the CB-kc high positive value (0.840) and the CB+Kc high negative value (-0.704). The slightly high or low positive values displayed the LS-kc and RS-kc and the CF+Kc. The eigenvalue is 2.557, which accounts for 15.984% of the contribution ratio. The lower PCS2 mainly indicated that the -kc and +Kc of the CB area are the higher values, and vice versa for the higher PCS2. The high or low values for the concave boundary waistline shape and the elliptical curved shape are extracted by PCS2. PC2 seems to be the factor responsible for the 3D skirt curved shape of the CB area.

PC3 included the LS+Kc slightly high negative value (-0.601) and the LS-Kc slightly low positive value (0.456). The eigenvalue is 1.562 and accounts for 9.761% of the contribution ratio. The lower PCS3 indicates the slightly high LS+Kc values, and vice versa for the lower PCS3. However, the LS-Kc represented the low mean and SD values of approximately 0, as previously listed in Table 2. The LS-Kc values in all 1,044 skirts do not make much of a difference depending on the PCS3 values. PC3 seems to be the factor responsible for the elliptical curved shape of the interior LS area.

PC4 and PC5 each included only the RS+kc, CB+kc, and CF+Kc slightly low positive value (0.467 to 0.528). As the +kc mean and SD values of those areas in Table 2 displayed approximately 0, each +Kc value for all 1,044 skirts exhibited no differences in the convex boundary waistline shape of the RS, CB, and CF areas under the PCS4 or PCS5 value. Therefore, PC4’s and PC5’s eigenvalues are 1.150 to 1.308 and accounts for 7.186% to 8.173% of the contribution ratios.

PC6 included only the RS+Kc slightly low negative value (-0.460). The lower PCS6 indicated that the RS+Kc are the higher values, and vice versa for the higher PC6. However, the eigenvalue (1.047) and the contribution ratio (6.545%) are low values.

Each single correlation between PCS1 to PCS2 and the female ages is represented by significant values (r = 0.340 to 0.344). The 3D skirt curved shapes appropriate for the female’s age will be extracted using the angles of concentrated Gaussian curvature Kc and concentrated geodesic curvature kc.

3.4 Classification of 3D tight-fitting skirt curved shape

In Fig. 5, the 3D curved shapes of the 1,044 3D skirts are categorized into 4 clusters at a branching level of approximately 7 dendrograms. The number of 3D skirts (N) in each cluster (78 \( \leq N \leq 475 \)) are considered using PCS1 to PCS3 (cumulative contribution ratio: 55.686%). The main features of the 3D skirt curved shape +Kc in the clusters shown in Fig. 5. Table 4 and Table 5 include ages show each mean and SD value of PCS1 to PCS3, the positive or negative deficit angles of the four areas (+Kc, -Kc, -Kc, and +Kc), and the number of 3D skirts in the four clusters. Furthermore, the significant differences that were determined by using a t-test between each cluster are displayed in Table 4 and Table 5 (*: \( p < 0.05 \), **: \( p < 0.01 \)). The mean values of PCS1 to PCS3 and female age in all the clusters show the significant differences between each cluster, with the exception of the mean

Table 4  Mean and SD values of PCS1 to PCS3 and ages in each cluster.

| Clusters | Means | SD | Ages |
|----------|-------|----|------|
| Cluster 1 | 0.327 | 0.605 | 0.975 | 42.69 |
| N = 238  | 0.598 | 0.707 | 0.543 | 17.92 |
| Cluster 2 | 0.799 | 0.723 | -0.231 | 59.77 |
| N = 253  | 0.570 | 0.995 | 0.965 | 19.26 |
| Cluster 3 | -1.962 | -0.091 | -1.000 | 31.13 |
| N = 78   | 0.873 | 0.710 | 0.871 | 10.57 |
| Cluster 4 | 0.061 | -0.703 | -0.103 | 36.82 |
| N = 475  | 0.833 | 0.618 | 0.705 | 15.17 |

| Clusters | 1 and 2 | ** | ** | ** |
|----------|----------|----|----|----|
| Clusters | 1 and 3  | ** | ** | ** |
| Clusters | 1 and 4  | ** | ** | ** |
| Clusters | 2 and 3  | ** | ** | ** |
| Clusters | 2 and 4  | ** | ** | ** |
| Clusters | 3 and 4  | ** | ** | ** |

Underlined and white boxed values show PCS1 to PCS3 of ±0.5; *: \( p < 0.01 \), **: \( p < 0.05 \).
values of PCS2 between cluster 1 and cluster 2 in Table 4. In Cluster 1 (N = 238, mean age values = 42.69 years old), PCS2 and PCS3 showed slightly higher positive mean values (0.605 and 0.975) in Table 4. As shown in Table 5, the LS-κc, RS-κc, and CB-κc of the concave boundary waistlines represented the minimum or second minimum mean values of all the clusters, while the LS+κc, RS+κc, and CB+κc of the elliptical curved shape displayed the minimum or second minimum mean values in all the clusters. However, the CF+κc of the elliptical curved shape showed a slightly high mean value of all the clusters. Therefore, Cluster 1 indicates the lowest or slightly low concave boundary waistlines and elliptical curved shapes of the LS, RS, and CB areas, and the slightly high elliptical curved shape of the CF area in all the clusters. Cluster 1 had the second lowest number of 3D skirts and the second oldest age group.

In Cluster 2 (N = 253, mean age values = 50.77 years old), PCS1 and PCS2 showed slightly higher positive mean values (0.799 and 0.723). The LS-κc, RS-κc, and CF-κc of the concave boundary line represented the highest or slightly high mean values of all the clusters, while the CB-κc of the concave boundary line displayed the lowest value of all the clusters. On the other hand, the LS+κc, RS+κc, and CF+κc of the elliptical curved shape represented the highest or slightly high mean values of all the clusters, while the CB+κc of the elliptical curved shape displayed the lowest value of all the clusters. Cluster 2 had the second highest number of 3D skirts and the oldest group. Therefore, Cluster 2 includes the 3D skirt curved shape of the oldest age group in all of the clusters, which was the highest or slightly high elliptical curved shapes and concave boundary waistlines in the LS, RS, and CF areas, and the lowest curved shapes with the elliptical curved shape and the concave boundary waistline in the CB area.

Cluster 3 (N = 78, mean age values = 31.19 years old) had the

![Fig. 5 Dendrogram obtained from factor loading using cluster analysis (Ward method) of 3D tight skirt curvatures κc and κe in each area.](image)

| Clusters | LS+κc | LS-κc | LS+κc | LS-κc | RS+κc | RS-κc | RS+κc | RS-κc | CB+κc | CB-κc | CB+κc | CB-κc | CF+κc | CF-κc | CF+κc | CF-κc |
|----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Cluster 1 Means | 0.008 | -22.500 | 23.239 | -2.385 | 0.016 | -22.560 | 23.345 | -2.460 | 0.031 | -12.188 | 19.245 | -2.340 | 0.082 | -9.186 | 9.356 | -1.890 |
| N = 238 SD | 0.102 | 4.619 | 4.566 | 1.501 | 0.095 | 5.493 | 5.205 | 1.904 | 0.072 | 3.795 | 6.404 | 1.818 | 0.506 | 4.977 | 5.233 | 2.264 |
| Cluster 2 Means | 0.008 | -22.500 | 23.239 | -2.385 | 0.016 | -22.560 | 23.345 | -2.460 | 0.031 | -12.188 | 19.245 | -2.340 | 0.082 | -9.186 | 9.356 | -1.890 |
| N = 253 SD | 0.013 | 4.201 | 5.730 | 1.351 | 0.056 | 5.493 | 5.948 | 1.243 | 0.046 | 4.170 | 6.241 | 1.190 | 0.001 | 7.573 | 8.324 | 1.065 |
| Cluster 3 Means | 0.005 | -24.594 | 28.408 | -7.031 | 0.090 | -19.850 | 24.075 | -7.807 | 0.114 | 3.545 | 7.091 | 3.095 | 1.679 | 3.602 | 3.280 | 1.670 |
| N = 78 SD | 0.003 | 6.050 | 6.534 | 3.061 | 0.293 | 5.218 | 5.315 | 2.913 | 0.004 | -2.617 | 2.728 | 1.090 | 0.106 | -2.384 | 2.844 | 3.379 | -3.819 |
| Cluster 4 Means | 0.005 | -31.087 | 31.891 | -2.843 | 0.006 | -30.171 | 30.812 | -2.831 | 0.044 | -16.230 | 25.689 | -2.578 | 0.106 | -9.394 | 8.370 | -1.555 |
| N = 475 SD | 0.002 | 6.532 | 6.654 | 1.770 | 0.027 | 6.322 | 6.528 | 1.608 | 0.010 | 3.354 | 6.457 | 2.127 | 0.042 | 5.967 | 5.809 | 1.214 |

** **: p < 0.01, *: p < 0.05
shown in Table 6. The values (%) in gray boxes in Table 6 show the
distributions in the total number of 3D skirts in each cluster are
30s in Cluster 4) were significant, as shown in Table 4. The age
differences of the mean age values between each cluster (early 40s
clusters, which was the lowest or slightly low elliptical curved shapes and concave
boundary waistlines in the LS, RS and CF areas and the highest elliptical curved shape in the CB area (Fig. 5).

In Cluster 4 (N = 475, mean age values = 36.82 years old), PCS2
showed only a slightly low negative mean value. Cluster 4 revealed
the second youngest mean age value and the maximum number of
3D skirts in all the clusters. The LS-Kc, RS-Kc, and CB-Kc of the
concave boundary lines and the LS+Kc, RS+Kc, and CB+Kc of the
elliptical curved shapes represented the highest or second highest
mean values of all the clusters. However, the CF+Kc of the elliptical
curved shape showed a slightly low mean value of all the clusters.
Cluster 4 includes the 3D skirt shape of the maximum number of
3D skirts, which was the highest or slightly high elliptical curved
shapes and the concave boundary waistlines in the LS, RS, and CB
areas and the slightly low elliptical curved shape in the CF area.

The similarities and differences in the 3D skirt curved shape
features between the four clusters are compared in Fig. 5. One of
the reasons for the differences in the features of the 3D skirt curved
shape in the four clusters is the wide range of age groups. The
differences of the mean age values between each cluster (early 40s
in Cluster 1, early 50s in Cluster 2, early 30s in Cluster 3, and late
30s in Cluster 4) were significant, as shown in Table 4. The age
distributions in the total number of 3D skirts in each cluster are
shown in Table 6. The values (%) in gray boxes in Table 6 show the
proportions of the number of 3D skirts in each age group of each
cluster to the total number of 3D skirts in each cluster (N of each
cluster). Furthermore, the values (%) in white boxes in Table 6 are
calculated proportions of the number of 3D skirts in each age group
of each cluster (AC of each cluster) to the total number of 3D skirts
in each age group (AT of each age).

The early 40s group in Cluster 1 and the early 50s group in
Cluster 2 displayed a similar low or slightly low elliptical curved
shape and slightly low concave boundary waistlines in the CB
areas, and vice versa for the high or slightly high elliptical curved
shape and concave boundary waistlines in the CB areas of the early
30s group in Cluster 3 and late 30s group in Cluster 4. The rate
of older female 3D skirts in Cluster 1 and Cluster 2 was higher
than that of younger female 3D skirts in Cluster 3 and Cluster 4,
as shown in Table 6. Furthermore, the early 50s group in Cluster
2, which had a high rate of females who were 50 to 59 and 70 to
84 years old, highly represented the elliptical curved shape and
concave boundary waistlines in the CF area toward the low or
slightly low 3D curved shapes in the same areas of the other three
clusters. The other three clusters were early 40s Cluster 1, early
30s Cluster 3, and late 30s Cluster 4 with the high rate of 18 to
29 to 40 to 49 young or slightly young age group. However, the
early 40s group of Cluster 1 and the early 30s group of Cluster 3
showed similarly low or slightly low elliptical curved shape and
slightly low concave boundary waistlines in the LS and RS areas.
The opposite was true for the high or slightly high elliptical curved
shape and concave boundary waistlines in the same areas for the
early 50s group, in Cluster 2, and the late 30s group, in Cluster 4. It
may be that the individual 3D body shapes of the LS and RS areas
are responsible for the similarities and differences in the 3D skirt
curved shape features between the four clusters. Furthermore, we
will investigate the big data of the 3D skirt curved shapes in the
older age and other age groups for estimating the custom-made 3D
and 2D tight-fitting skirt.

| Ages | AT (number of 3D skirt) | Cluster 1 (N = 238, 42.69 years) | Cluster 2 (N = 253, 56.77 years) | Cluster 3 (N = 78, 31.13 years) | Cluster 4 (N = 475, 36.82 years) | AT (%) |
|------|------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|--------|
| 18-29| 344                    | 29.41                           | 20.31                           | 21.74                           | 15.90                           | 51.28  | 11.59  | 38.53  | 52.20  | 100.00 |
| 30-39| 232                    | 17.23                           | 17.97                           | 13.04                           | 14.92                           | 25.64  | 8.84   | 28.21  | 58.27  | 100.00 |
| 40-49| 155                    | 20.17                           | 30.97                           | 11.46                           | 18.71                           | 16.67  | 8.39   | 13.68  | 41.94  | 100.00 |
| 50-59| 82                     | 9.66                            | 28.05                           | 8.30                            | 25.61                           | 5.13   | 4.88   | 7.16   | 41.46  | 100.00 |
| 60-69| 131                    | 13.45                           | 24.43                           | 23.32                           | 45.04                           | 1.28   | 0.76   | 8.21   | 29.77  | 100.00 |
| 70-84| 100                    | 10.08                           | 24.00                           | 22.13                           | 56.00                           | 0.00   | 0.00   | 4.21   | 20.00  | 100.00 |
| Total number of 3D skirt and rate (%) | 1044 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

AT: Total number of 3D skirts in each age group; AC: Total number of 3D skirts in each age group of each cluster. Underlined and bold values show maximum and minimum respectively.
4. Conclusions

To create an automatic 3D tight-fitting skirt making system for the 3D body surface shapes via computer simulation based on the support information, the 3D skirt curved shapes with 2D pattern shape data of 1,044 females were extracted via the vertex angles of the dividing triangle meshed 3D skirt surfaces without using cloth or the need to sew a skirt. The deficit angle values of the concentrated Gaussian curvature \( Kc \) \((360° \cdot (2\pi - \theta n)\) on the interior area vertexes and the concentrated geodesic curvature \( kc \) \((180° (\pi \cdot \theta n)\) on the exterior boundary line vertexes enabled us to extract the 3D skirt curved shapes (+\( Kc \): elliptical, -\( Kc \): hyperbolic, and \( Kc = 0 \): developable surfaces) and the 3D skirt boundary line shapes (+\( kc \): convex, -\( kc \): concave, and \( kc = 0 \): straight lines) with the 2D development pattern shape data.

Each total angle value of the Sum \( Kc \) (mean value = 80.18°) and Sum \( kc \) (mean value = -80.18°) in all the 3D skirts was determined to be “zero” based on the conservation law according to the Gauss-Bonnet theorem. The distribution of the \( Kc \) and \( kc \) values was able to represent the 3D skirt curved shapes independent of the 3D skirt sizes without sewing the skirt. The 3D skirt curved shape was formed using the higher elliptical curved shape and concave boundary waistline on the left and right side (LS and RS) areas, the slightly high elliptical curved shape and concave boundary waistline on the center back (CB) area, and the lower elliptical and concave boundary waistline on the center front (CF) area according to the mean values gathered in this study. All the boundary hemlines of the 1,044 3D skirts showed a straight line shape (\( kc = 0 \)).

The 3D skirt curved shapes of the 1,044 females using the four curvatures, +\( Kc \), -\( Kc \), +\( kc \), and -\( kc \) on the four areas (LS, RS, CB, and CF) were categorized using a cluster analysis based on a PCA. The principal components, PC1 to PC6 (cumulative contribution ratio: 77.591%), of mainly the +\( Kc \) and -\( Kc \) of the elliptical curved shapes and concave boundary waistlines on the four areas were extracted. PC1 mainly represents the factor responsible for the 3D skirt curved shape of the -\( kc \) and +\( kc \) on all areas except -\( kc \) in the CB area. PC2 represents the factor responsible for the 3D skirt curved shape of the -\( kc \) and +\( Kc \) on the CB area, while PC3 represents the factor responsible for the elliptical curved shape of the LS area. The cluster groups were made using PCS1 to PCS3.

The 1,044 3D skirts were divided into Cluster 1 (\( N = 238 \), mean age values = 42.69 years old), Cluster 2 (\( N = 253 \), mean age values = 50.77 years old), Cluster 3 (\( N = 78 \), mean age values = 31.19 years old), and Cluster 4 (\( N = 475 \), mean age values = 36.82 years old) using PCS1 to PCS3. The four 3D skirt curved shapes were extracted and included the different age groups: the 3D skirt curved shape for the old female in their early 50s with the high elliptical curved shape and concave boundary waistlines of the LS, RS, and CF areas and the low versions of those shapes of the CB area in Cluster 4; the 3D skirt curved shape for the young female in their early 30s with the low elliptical curved shapes and concave boundary waistlines of the LS, RS, and CF areas and the high or slightly high versions of those shapes of the CB area in cluster 3; the slightly old female in their early 40s with the slightly high elliptical curved shapes and concave boundary waistlines of the CB area and the slightly low versions of those shapes of the LS, RS, and CB areas in Cluster 1; and the 3D skirt standard curved shape for the slightly young female in their late 30s with the slightly low elliptical curved shape and concave boundary waistline of the CF area and the high or slightly high versions of those shape of the LS, RS, and CB area in Cluster 4.

We created the different 3D skirt curve shapes between the CF and CB areas according to the different age groups. The 2D skirt pattern that reflects 3D skirt curved shapes can be used to easily design skirts without making patterns. Furthermore, we have now conducted research on the 3D garment and body curved shapes for \( Kc \) and \( kc \) based on individual differences, including age, among many females.

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