Utilising finite element analysis to evaluate gore design in bras

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ABSTRACT – REZUMAT

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In the early stage of bra pattern making, the gore size is an important design feature to provide different effects such as enhancing the shape of the breasts and the depth of the cleavage, as well as affecting the fitting issue. However, the shaping effects in controlling the breast shape of the gore size have not been investigated in previous studies. This study proposes a finite element method (FEM) to simulate the effect of gore dimensions on breast shape in a wired-bra. A biomechanical model based on accurate geometries and mechanical properties of humans is first built. Then, the sub-model of a bra with different gore design scenarios interacts with the sub-model of the human body. A factorial analysis has been conducted that the effects of lengths of the upper gore and lower gore on the breast geometry are systematically investigated based on the numerical contact models. The length of the upper gore positively contributes to the gathering of the breasts and a deeper cleavage. While the length of the lower gore has a negative relationship with the lifting effect of the breasts and the position of the bra underwire. Reduced lower gore length would lead to a poor fit of the underwire against the breast roots. The method proposed in this paper can be used by bra designers to predict the breast deformation, and thus reducing the time required for the designing of pattern making at the early stages.

Keywords: *gore, finite element, bra design, shaping effects, factorial analysis*

Utilizarea analizei cu elemente finite pentru evaluarea designului benzii dintre cupe la confecționarea sutienului

În faza incipientă a modelului de sutien, dimensiunea benzii dintre cupe este o caracteristică importantă de design pentru a oferi diferite efecte, cum ar fi îmbunătățirea formei sânilor și adâncimii decolteului, precum și soluționarea problemei de potrivire. Cu toate acestea, efectele modelării în controlul formei sânilor în raport cu dimensiunea benzii dintre cupe nu au fost investigate în studiile anterioare. Acest studiu propune o metodă a elementelor finite (FEM) pentru a simula efectul dimensiunilor benzii dintre cupe asupra formei sânilor în cazul unui sutien cu armătură. Mai întâi este construit un model biomecanic bazat pe geometrii precise și pe proprietățile mecanice ale corpului uman. Apoi, submodelul de sutien cu diferite scenarii de design al benzii dintre cupe interacționează cu submodelul corpului uman. S-a efectuat o analiză factorială conform căreia lungimile benzii superioare și a celei inferioare dintre cupe în raport cu geometria sânilor sunt investigate sistematic pe baza modelelor numerice de contact. Lungimea benzii superioare dintre cupe contribuie pozitiv la strângerea sânilor și la un decolteu mai profund, în timp ce lungimea benzii inferioare dintre cupe are impact negativ asupra efectului de ridicare al sânilor și poziției armăturii sutienului. Reducerea lungimii benzii inferioare dintre cupe ar duce la o potrivire slabă a armăturii la baza sânilor. Metoda propusă în această lucrare poate fi folosită de designerii de sutiene pentru a anticipa deformarea sânilor și, astfel, pentru a reduce timpul necesar pentru proiectarea modelelor în stadiile incipiente.

Cuvinte-cheie: *bandă dintre cupe, element finit, design al sutienului, efecte de modelare, analiza factorială*

INTRODUCTION

A good-fitting bra is expected to support the breasts against the effects of gravity and provide an aesthetically pleasing profile. The tension between the breasts and bra fabric is caused by the fabric's stress-strain properties and the pattern design is an important element for achieving the desired shape and amount of support for the breasts [1]. To make each bra cup located in the right position along the under-breast contour, the gore which is a rigid centre panel is used to connect two bra cups in the centre front [2]. A proper gore design can effectively hold a bra in place and even contribute to pushing up the breasts. The best-fitting gore should sit against the sternum, allowing the wearer to breathe normally [3]. The gore size, including the gore width and height, is an important bra design feature in the early stages of pattern making. Changing the gore width could provide different effects, such as enhancing the shape of the breasts and the depth of the cleavage. Increasing the gore height may also be associated with wear discomfort and make the bra style old-fashioned [4]. In traditional bra manufacturing, pattern development involves iterative processes, also called 'trial and error', to first make a prototype and then fit it to a model to check each feature. It will take a lot of repetitive work and be burdensome to do the fitting evaluation and pattern adjustment [5]. Computational technology can aid garment development, thus reducing the time and expense of the fit trial. On the other hand, the strain of the garment, the deformation of the human body and the contact pressure between the garment and the body can be systematically quantified [6]. The computational technique of Finite Element Method (FEM) has been used in the design and development processes of the fashion industry. FE simulation allows for a customer-specific model that incorporates real detailed information about the customer and analyses individual responses in terms of body reshaping and comfort pressure while fitting different garments [7–9]. About the bra design by the FE method, Bruno [10] numerically modelled bras and investigated the effects on breasts during exercise. Sun and her team [11, 12] developed an FE contact model to simulate the process of bra wearing and evaluate the breast shaping effects and pressure value of different bra features, such as cup fabrics and types of bras (with or without underwire). Zhang [13] proposed a numerical model to simulate the interaction of the bra strap and the movement of the upper body. The bra straps with different design features were evaluated based on the FE model. However, the effects of bra components such as gore size on controlling the breast shape and providing adequate support have not been fully investigated. Table 1 provides a summary of the researches on FEM used in garment design.

This paper proposed a numerical method to simulate the effect of gore dimensions on breast shape when a wired-bra is worn, thus providing useful information to bra designers to advance the design and shaping performance of wired-bras.

METHODS

Experiments

A 3D body scanning experiment by a 3D laser body scanner (Vitus, Human Solutions, Germany) was conducted to record the breast shape of a healthy 45-year-old woman after wearing a soft bra with a single-layer structure. The purpose of the soft bra was to find breast roots easily in the 3D digital image so that the breast volume was accurate in the modelling. The height of the subject was 166 cm and the weight was 61.2 kg. In the metric sizing system, her bra size was 36C. The experiment was approved by the University Human Subjects Ethics Committee.

Materials

In the current study, the bra sub-model was simplified as strapless to reduce the simulation time. The nodes at the top of the bra cups were fixed to apply the same effect as having the straps during the simulation instead of incorporating them. The bra structure built in this study is shown in figure 1.

The bra sample constructed for the FE simulation in this study was non-woven fabric for the cup and elastic fabric for the band. The gores were considered as

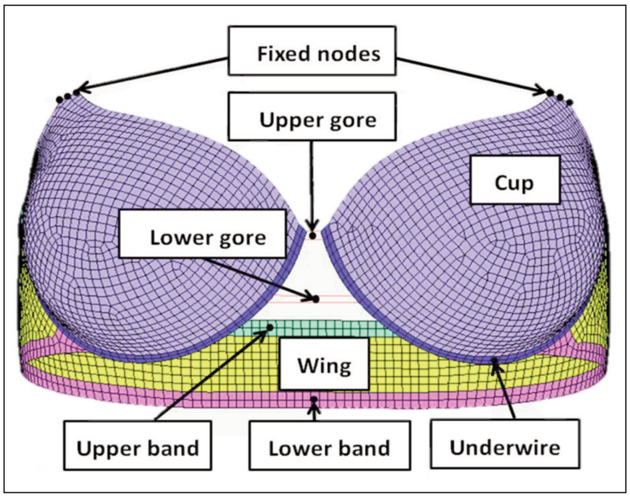

Fig. 1. Sub-model of bra without straps

Table 1

SUMMARY OF THE STATE-OF-THE-ART RESEARCH ON FEM USED IN GARMENT DESIGN					
Sr No	**Reference**	**Kind of garment**	**Design feature**	**Body modelling**	**Garment modelling**
1	[7]	Pantyhose and T-shirts	Fabric material model	Rigid	Rebar layer model & isotropic hyperelastic matrix
2	[8]	Gilet and one-piece dress	Fabric material	Shell element; linear elastic, isotropic	Shell element, linear elastic; orthotropic
3	[9]	Shoe	Sole thickness and material	Solid element; linear, elastic and isotropic (bone, ligament and cartilaginous structures), hyper-elastic (foot soft tissue)	Solid element; non-linear incompressible hyper-elastic
4	[10]	Bra	-	Solid element; hyper-elastic	Shell element
5	[11]	Bra	-	Solid element; hyper-elastic	Shell element; linear elastic; orthotropic
6	[12]	Bra	Bra cup material	Solid element; hyper-elastic	Shell element; linear elastic; orthotropic
7	[13]	Bra	Bra strap width, spacing, elongation, friction and Young's modulus	Rigid	Shell element; linear elastic; isotropic

Table 2

MECHANICAL PROPERTIES FOR EACH BRA COMPONENT						
Bra components	**Young's modulus (MPa)**		**Shear modulus (MPa)**		**Poisson ratio**	
Cup	Course direction	Wale direction	Course direction	Wale direction	Course direction	Wale direction
	3.68	4.68	0.24	0.29	0.31	0.25
Gore	210000		78900		0.33	
Underwire	210000		78900		0.33	
Band	0.90		0.35		0.28	
Wing	0.10		0.04		0.25	

rigid lines with high stiffness. The mechanical properties for each bra component are given in table 2.

As mentioned in our previous work on the human body modelling, the material properties of soft breasts tissues [11, 12] were assumed to be isotropic and homogeneous with uniform structure inside the breast. The breast tissue was regarded as a non-compressive material with non-linear property. The hyper elastic material model was utilised to describe the behaviour of the breast tissues. The non-linear property of this material type can be defined as the strain energy density function by equation 1.

$$W(I_1,I_2) = \sum_{i,j=0}^{n} C_{ij}(I_1-3)^i(I_2-3)^j \quad (1)$$

where C_{ij} are the hyper-elastic material coefficients to characterise the nonlinear behaviour of breast deformation. I_1 and I_2 are the first and the second invariants of the components of the left Cauchy-Green deformation tensor B, as given in equation 2.

$$I_1 = \mathrm{tr}(B)$$
$$I_2 = \frac{1}{2}\left[(\mathrm{tr}(B))^2 - \mathrm{tr}(B^2)\right] \quad (2)$$

where $B = F \cdot F^T$, F is a deformation gradient.

When n is equal to 2, the material property can be described as the Mooney-Rivlin model with five coefficients (C_{10}, C_{01}, C_{11}, C_{20}, and C_{02}). The specific details of each coefficient are given in table 3 below.

Table 3

MATERIAL COEFFICIENTS FOR BREAST TISSUES	
Parameter	**Value**
Density (kg/m^3)	1000
C_{10}	0.05
C_{01}	0.052
C_{11}	0.375
C_{20}	0.78
C_{02}	0.63

Construction of gore designs with different scenarios

Construction of the sub-model of bra started from the stress-free state process which can be obtained by the method proposed in our previous study [11]. The initial 3D bra model (figure 1) was subtracted from the three-dimensional image of the subject and the wearing tension of the bra was then released by the steps of cutting 20% length of the band, relaxing the opening force of underwires and flattening the 3D structure of band and underwires. The shape of the gore normally resembles a trapezoid shape. To simulate the effects of different gore designs, two individual design parameters (length of the upper and lower parts of the gore) were used to determine the gore shape. To obtain the initial geometric model of the bra with a specific length of the upper or lower part of the gore, a base model (GM0) with the length of the upper 10 mm and lower parts of the gore 35 mm was first constructed. Another scenario with the shorter (GM1) upper part of the gore can be obtained based on GM0 by rotating the right part of the bra against P_1 with a negative angle and the left part of the bra against P_2 with a positive angle in the *xoy* plane (figure 2). After this step, the length of the upper part of the gore can be modified with the rotation angle until the desired value is reached, while the length of the lower gore remains the same as its initial length.

Similarly, a model of the lower part of the gore which is shorter (GM2) can be obtained by rotating the right

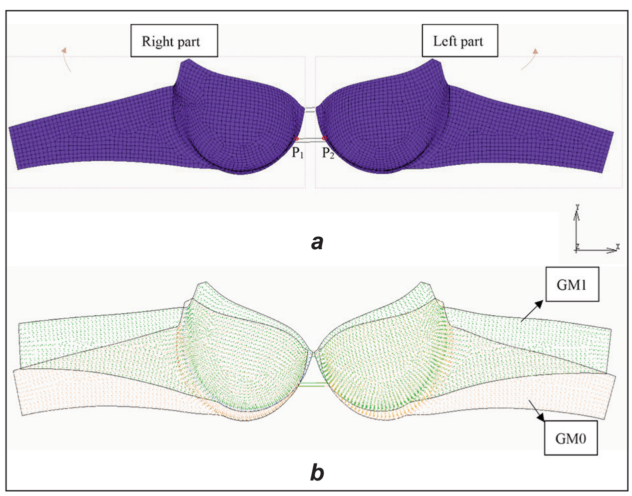

Fig. 2. Process of converting initial sub-model of bra to shorter gore (upper part): *a* – process of obtaining bra model with shorter gore (upper part); *b* – obtained sub-model of bra with shorter gore (upper part)

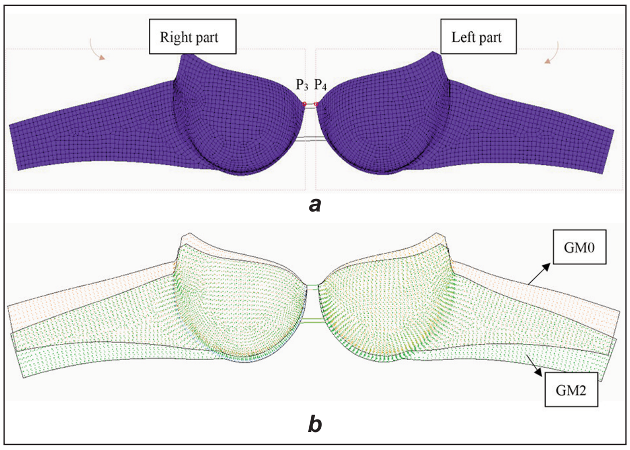

Fig. 3. Process of converting initial sub-model of a bra to shorter gore (lower part): *a* – process of obtaining a model of a bra with shorter gore (lower part); *b* – obtained sub-model of a bra with shorter gore (lower part)

part of the bra against P_3 with a positive angle and the left part of the bra against P_4 with a negative angle in the *xoy* plane. The process is presented in figure 3.

The geometric sub-model of a longer gore (upper and lower parts) was obtained by following the steps in figures 2 and 3 in the opposite rotated directions, respectively.

FEM simulation

Yu [3] reported that the gore size can lead to a change in breast shape, such as the gathering of the breasts and depth of the cleavage. However, studies in the current literature have not examined how the design parameters of the gore affect the shaping effects of a bra. To address this research gap, numerical simulation is considered to be more advantageous over wear trials, not only because it is an efficient tool to plan and visualise the design problem,

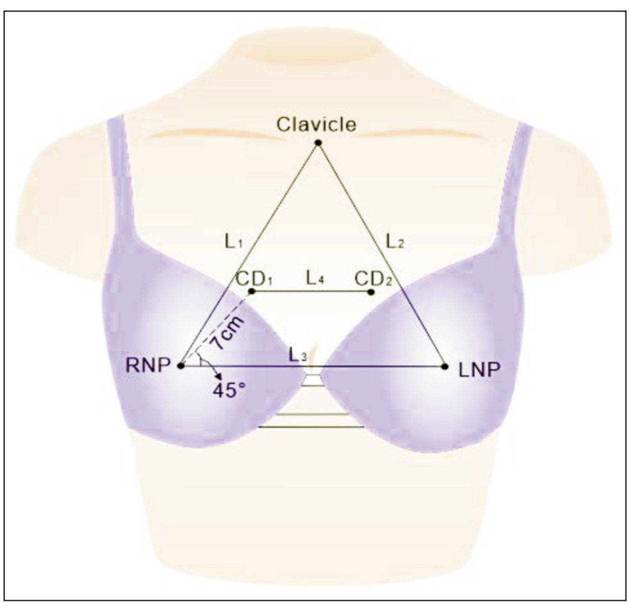

Fig. 4. Body measurements to determine the breast shaping

but also reduces time-consuming tasks such as preparing multiple design features and carrying out repetitive measurements in experiments. The simulation process of wearing a bra in a commercial FE modelling software (MSC. Marc 2014.2.0, US) has been reported in our previous study and the method has been proved to be accurate within an acceptable range in simulating the shaping effects of breasts after wearing different types of bras [11, 12]. The indicators related to the shape of the breasts applied the body measurements of L_1, L_2, L_3 and L_4 to evaluate the lifting and gathering effects. The items RNP, LNP and CD_i (i = 1 or 2) represent the right nipple point, left nipple point and cleavage dots, respectively.

Factorial design and analysis

The length of the upper and lower parts of the gore is considered to be the two fixed factors in a factorial analysis. According to the bra fitting criterion, the length of the upper part of the gore cannot exceed the width of the sternum (which is 20 mm in the model in this study). Thus, the maximum length of the upper part of the gore in the simulation is 20 mm. The factorial design in this study includes two factors each at four levels or a 4×4 simulated factorial experiments. The relationship between the real values of the gore length and the coded levels of the input variables in the factorial analysis is determined by using the following equation:

$$A_i = \frac{a_i - a_c}{\Delta a} \quad (i = 1, 2, 3, 4) \tag{3}$$

where A_i is the coded level of the input variable (length of upper and lower parts of gore); a_i is the real value of the variables; a_c is the real value of the length of the centre of the gore and Δa is the interval between the adjacent real values. The four coded levels are: low (–1), centred (0), moderately high (1) and high (2), respectively. The interval of each level for the upper part of the gore is 5 mm, while that of the lower part of the gore is 10 mm. The difference in the height between the upper and lower parts of the gore is a fixed value of 4 mm. The parameters and their factor levels are listed in table 4.

Table 4

FACTOR LEVELS OF GORE

Parameter	Symbol	Level (code)			
		–1	0	1	2
The upper part of the gore	U	5 mm	10 mm	15 mm	20 mm
The lower part of the gore	B	25 mm	35 mm	45 mm	55 mm

Table 5 shows the response results of the 16 runs of the simulation with both variables. The results of each run do not vary and with no random errors because the numerical simulation has no repeatability errors under the same parameter input.

Table 5

DESIGN MATRIX AND RESULTS OF 16 RUNS OF SIMULATION						
No.	**U**	**B**	**L_1 (mm)**	**L_2 (mm)**	**L_3 (mm)**	**L_4 (mm)**
1	–1	–1	242.605	242.393	199.58	98.3863
2	–1	0	243.021	242.355	203.076	100.066
3	–1	1	240.456	239.925	198.998	97.0353
4	–1	2	241.374	241.167	201.471	102.367
5	0	–1	247.204	247.419	202.044	99.3466
6	0	0	242.287	241.724	204.625	102.018
7	0	1	242.253	242.802	207.403	103.51
8	0	2	237.751	237.689	208.184	101.965
9	1	–1	249.231	249.458	204.278	103.738
10	1	0	247.64	247.088	207.201	104.322
11	1	1	243.33	243.149	207.745	103.018
12	1	2	236.502	235.509	206.286	98.3262
13	2	–1	250.31	250.697	206.836	105.527
14	2	0	248.514	248.824	209.583	105.946
15	2	1	248.427	248.253	210.211	106.513
16	2	2	244.485	244.149	210.309	104.796

RESULTS AND DISCUSSION

Correlation analysis

A correlation analysis was conducted to determine the statistical relationships between the gore size and the shaping effects on the breasts (output). Pearson's correlation coefficients were calculated to verify the correlations. Table 6 provides the correlation coefficient values and significance. It can be observed that there is a statistically significant correlation between U and L_3 and L_4 (Pearson correlation coefficient r = 0.836 and P value $p < 0.01$) and a considerably significant negative correlation between B and L_1 and L_2 ($r = -0.663$; $p < 0.01$).

In table 6, it can be observed that there is a statistically positive relationship between the length of the upper part of the gore and L_3 and L_4 (r = 0.836, $p < 0.01$), which means that a shorter gore (upper part) results in a decrease in L_3 and L_4. When the upper part of the gore is considered to be a single variable in the design parameters, shortening its length has a more significant influence on the gathering than the lifting of the breasts. Two simulated cases of the upper part of the gore (i.e., $U = 1$, $B = 1$ in figure 5, *a*; $U = 0$, $B = 1$ in figure 5, *b*) are shown in figure 5 to visually show the relationship.

Figure 5 shows the displacement in the x direction and the deformation maps have the same contour scale. The former shows that when the length of the upper part of the gore is equal to the width of the sternum (which is 20 mm here), the amount of deformation at the bottom of the breasts in the horizontal direction is almost the same as that in the gravity-free state. By shortening the upper part of the gore, there is a gathering at the bottom of the breasts (see yellow and blue colours in the deformation map of figure 5, *b*).

The inverse correlation between B and L_1 and L_2 ($r = -0.663$; $p < 0.01$) shows that increasing the length of the lower part of the gore improves the lifting of the breasts. This is probably because a shorter length of

Table 6

CORRELATION ANALYSIS					
Variable	**Item**	**Output**			
		L_1	L_2	L_3	L_4
U	Pearson's correlation	0.561*	0.554*	0.836**	0.763**
	Sig. (2-tail)	0.024	0.026	0.000	0.001
	N	16	16	16	16
B	Pearson's correlation	–0.663**	–0.662**	0.313	–0.062
	Sig. (2-tail)	0.005	0.005	0.238	0.821
	N	16	16	16	16

Note: * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

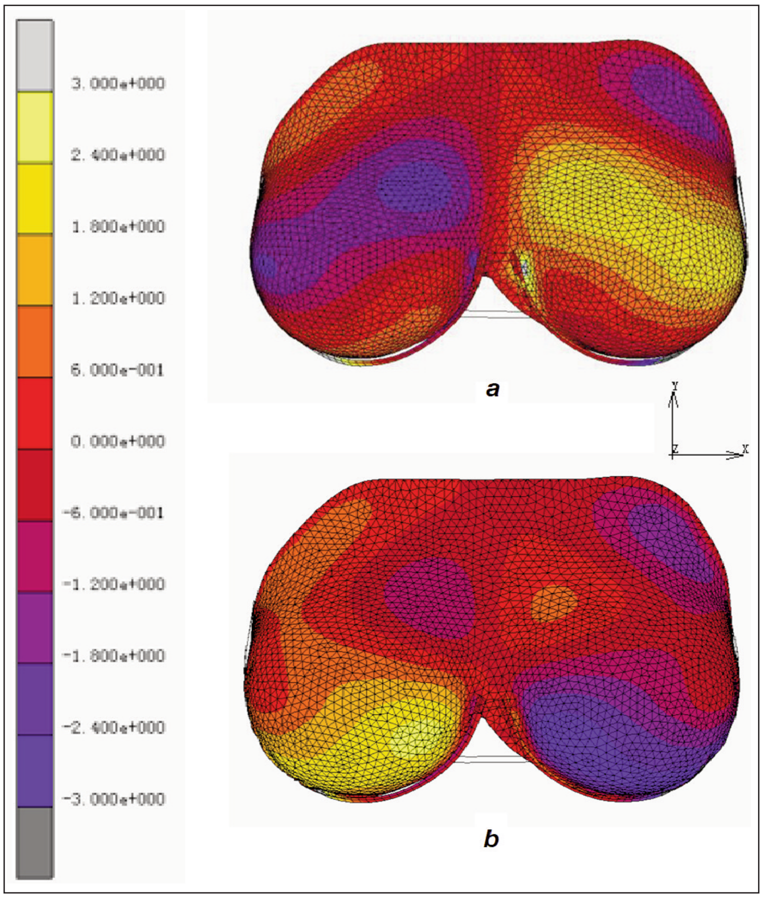

Fig. 5. Two simulated cases with different lengths of upper part of gore (unit of contour bar: mm): *a* – *U* = 1, *B* = 1; *b* – *U* = 0, *B* = 1

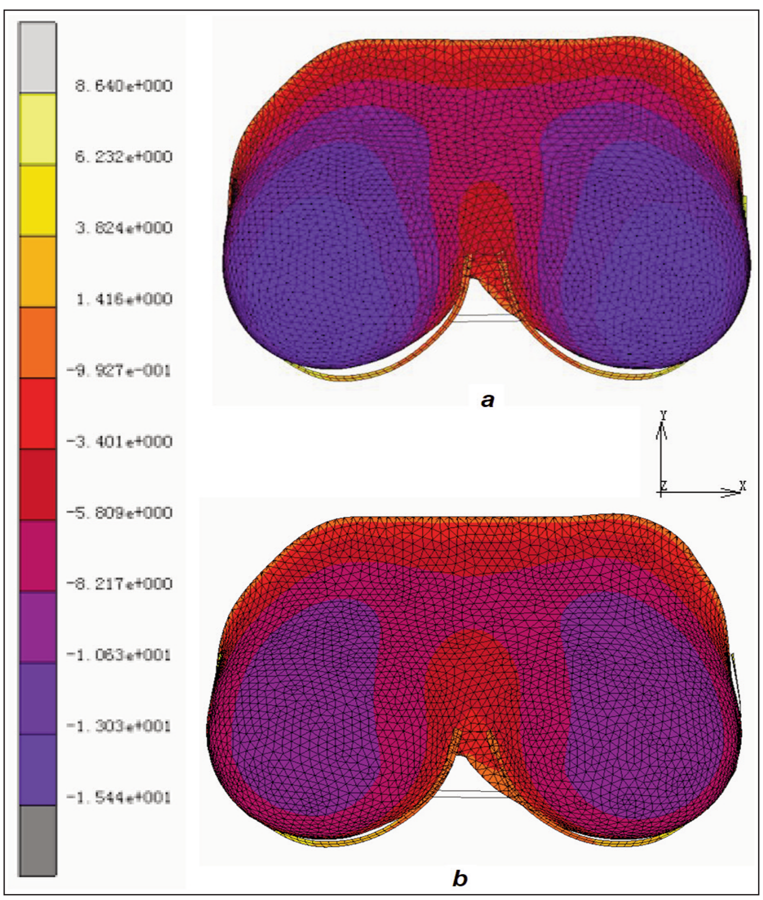

Fig. 6. Two simulated situations with different lengths of the lower part of gore (unit of contour bar: mm): *a* – *U* = 1, *B* = 0; *b* – *U* = 1, *B* = 1

the gore (lower part) causes a fitting problem in which the underwire does not align with the breast roots. Figure 6 provides examples of two lengths of the lower part of the gore. The deformation map shows displacement in the *y* direction. A darker colour indicates a greater degree of sagging phenomenon. It can be observed that when the length of the lower part of the gore is 45 mm, there is a better fit against the breast roots as opposed to a shorter gore of 35 mm. This better-fit results in raising the lift of the breasts.

Regression model

To establish a response model to approximately predict the shaping of the breasts with different combinations of the length of the upper and lower parts of the gore, a mathematical equation was established with two linear terms – one interaction term and one intercept term as follows:

$$f = \alpha_0 + \alpha_1 U + \alpha_2 B + \alpha_3 UB \quad (4)$$

where *f* is the measured area of the body (L_1, L_2, L_3 and L_4) which represents the shape of the breasts after wearing a bra. Table 7 shows the significance level of each item by listing the coefficients (α_0, α_1, α_2 and α_3 in equation 2), standard errors (S.E.), T-value (T-test value) and P-value (probability of obtaining a certain confidence level). The R^2 and R^2_{adj} are also given to evaluate the fit of the regression model.

Based on the coefficients in table 5, the approximate models for the four measurements are described by Eq. (5a) – (5d), and the resultant models can predict the response to the two parameters of the upper and lower parts of the gore with an accuracy of 77.7%, 77.7%, 80.2% and 64.8% respectively.

$$L_1 = 244.150 + 2.241U - 2.128B - 0.48UB \quad (5a)$$

$$L_2 = 243.968 + 2.395U - 2.206B - 0.60UB \quad (5b)$$

$$L_3 = 203.710 + 2.549U - 0.942B - 0.137UB \quad (5c)$$

$$L_4 = 101.203 + 2.226U - 0.270B - 0.585UB \quad (5d)$$

CONCLUSION

In this study, based on FEM, the changes in breast shape about the upper and lower widths of the gore panel are systematically reviewed. The results of a correlation analysis show that the length of the upper part of the gore positively contributes to

Table 7

SIGNIFICANCE LEVEL OF EACH FACTOR						
Term	Coefficient	S.E.	T-value	P-value	R^2	R^2_{adj}
(L_1)					0.777	0.721
Constant	244.150	.653	373.857	0.000		
U	2.241	.533	4.203	0.001		
B	–2.128	0.533	–3.990	0.002		
*U*B*	–0.480	0.435	–1.103	0.292		
(L_2)					0.777	0.721
Constant	243.968	0.692	352.310	0.000		
U	2.395	0.565	4.237	0.001		
B	–2.206	0.565	–3.901	0.002		
*U*B*	–0.600	0.462	–1.300	0.218		
(L_3)					0.802	0.753
Constant	203.710	0.540	377.204	0.000		
U	2.549	0.411	5.780	0.000		
B	0.942	0.441	2.135	0.054		
*U*B*	0.137	0.360	0.381	0.710		
(L_4)					0.648	0.560
Constant	101.203	0.582	173.800	0.000		
U	2.226	0.475	4.682	0.001		
B	0.270	0.475	0.568	0.581		
*U*B*	–0.585	0.388	–1.507	0.158		

the gathering of the breasts, thus resulting in a deeper cleavage. The length of the lower part of the gore has a negative influence on the lifting of the breasts and the position of the bra underwire. A shorter length would lead to a poor fit of the underwire against the breast roots. Regression models of four measurements of different parts of the body are established to approximately estimate the output response (breasts) to the different combinations of design parameters of the bra gore. This study has confirmed that FEM is a useful tool that can be used by bra designers to predict the amount of breast deformation, and thus reduce the time required for the designing at the early stages of pattern making in manufacturing. However, a more realistic model of the human body and sub-model of bras with various design parameters (such as underwire shape, material property of the underwire and orientation of bra straps) should be constructed in future studies to enhance the understanding of the interaction process between the breasts and bra.

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