Finite Element Analysis on Contact Pressure and 3D Breast Deformation for Application in Women's Bras

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Abstract: A well-fitting bra provides adequate and exceptional support of the breasts and the desirable body shape for the wearer but would not exert excessive pressure onto the breasts. Among the different design features of bras, the materials selected for the bra cups are a key element for enhancing breast support and improving the perceived comfort. This paper proposes a subject-specific model based on numerical simulation to investigate the influence of different types of bra cup materials on the shape of the breasts and amount of pressure on the breasts. The study comprises three phases. The first phase is the development of a subject-specific contact model and simulation of the bra-wearing process. The second phase is the construction and analysis of three models with different bra cup materials (knitted, woven and foam) to compare their shaping effects on the breasts and the corresponding amount of applied contact pressure. The third phase uses the validated numerical model to simulate the use of a series of virtual bra cup materials, their impact on the shape of the breasts, and the associated bra pressure. It is found that a stiffer fabric has a better performance in reshaping the breasts and reducing the amount of pressure from the straps onto the neck for a halter-neck bra but distributes a higher amount of pressure at the bottom part of the breasts. An overall better performance of reshaping the breasts is achieved by increasing the tensile strength of the bra cup material. Nevertheless, the small change in the shaping effects can be negligible after the Young's modulus reaches about 1.5 MPa. Among the four measured variables, it is more useful to measure the gathering of the breasts and depth of cleavage than the lifting of the breasts to determine the amount of breast deformation caused by a bra. The newly developed finite element model for contact analysis in this study provides a better understanding on the interactive process between the breasts and the bra by predicting the deformation within a variance of 6.8 % in comparison to the experimental results of the contact pressure with the same trend and magnitude. Numerical simulations can therefore facilitate decisions on the type of fabric used for bra designs that provide optimal fabric pressure and other stretchable apparel products that take both the shaping effect and wear comfort into consideration.

Keywords: Finite element method, Cup material, Bra design, Shaping effect, Pressure

Introduction

There is a great demand among female consumers to have their daily-wear bra meets their needs for fit, comfort and body reshaping [1]. A well-designed bra is expected to accommodate the breast contours well and not apply excessive contact pressure [2]. The bra cups are a key component of bras, and often fabricated with rigid materials to enhance the support of the breasts and shape them. Well-fitting bra cups provide adequate and exceptional support without applying excessive pressure, and evenly distribute the weight of gravity [3]. Due to the complexities of the compression and pulling forces of the close-fitting bra components, an improper design and selection of materials will affect the overall support performance of the bra [4]. A good bra design not only requires a pattern that is anatomically engineered, but also incorporates the effects of the fabric properties and their stress-strain behavior [2]. In traditional cut-and-sewn bras, rigid bra cup fabrics such as low-stretch satins, 50-denier nylon tricot, and lace are commonly used to control excessive breast movement [5]. With advances in knitting technology, textured nylon yarns and stretch elastane yarns are often used to provide different levels of support to the breasts, softness and comfort [6,7]. The literature on the use of polyurethane (PU) foam in moulded bra cups has also indicated that the physical properties of PU such as density, tensile strength, compression stress, etc., have a major influence on the performance behavior of the bra cups, thus affecting the shaping effects and contact pressure during wear [8].

Breast deformation and pressure on the skin due to bra wear are complex contact problems, but examining the mechanical interaction between the breasts and bra can provide the criteria for selecting the optimal fabric for a bra [9]. For example, the pressure exerted onto the body depends on the curvature and contours of the body and the tension of the bra fabric. Fabrics with a high Young's modulus, however, may exert more pressure onto the body [10]. For instance, the fabric for compression sports bras requires different optimal mechanical properties, such as adequate elasticity to enable upper torso movement while allowing the chest to expand for breathing. The fabric should

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*Corresponding author: tcyick@polyu.edu.hk also offer excellent recovery to prevent excessive displacement of the breasts. Otherwise, the material fails to meet the requirements and expectations of users for body shaping, and instead leads to breast pain. Zhuo *et al*. [11] conducted an experiment on bra fit with three subjects and five commercial bras fabricated with different elastic materials to observe the influence of fabric elongation on contact pressure values. They found that a fabric with lower tensile resistance results in lower contact pressure. Lu *et al*. [12] investigated the effects of the material of sports bra cups to control breast movement during exercise. The mechanical properties of three types of sponge materials used for the bra cup padding are tested with extension and compression testers. The results show that the bra fabric is not only important for reducing the amount of breast displacement, but also affects the comfort pressure of the wearer, so they recommend taking the tensile and compression properties of bra materials into account. However, the current literature has only examined the influence of the mechanical properties of a fabric on the body and the amount of pressure induced during wear trials involves human intervention, and the types of fabrics tested are very limited, which mean that the results cannot be generalized nor are they conclusive.

Traditionally, manufacturers in the bra industry use many procedures to develop a pattern and select fabric to construct bras. This is not only time-consuming but also expensive as trial and error are usually used in the fabrication process from developing a prototype to constructing the final product [13]. Also, manufacturers spend utmost effort to keep pace with the dynamic market changes, and to do so, they use advanced technologies for the design and development of bras. One of these technologies is numerical modeling by using the finite-element (FE) method. This method is suitable for use in the intimate apparel field because the method can address key challenges including the non-linear material properties of the breast tissue, orthotropic properties of the bra cup materials and the complex mechanical interactions between the body and bra [14]. Zhang [15] first provided a numerical model of the human body and a garment using the FE method. The garment was meshed as an elastic shell with geometric nonlinearity and the body was assumed to be rigid which did not deform during the wear process. The contact between the body and garment was simulated as a sliding interface. Although they used the numerical model to test the properties of different materials for the garment and determine their mechanical properties which would affect the contact pressure between the garment and body, nevertheless, they compared different contact pressures on a rigid body which is not realistic. Liu [16] used FE contact models to calculate the pressure of clothing on the bust with 10 sports vests that have different fabric material properties. The relationships between clothing pressure on the bust and garment bust strain, as well as Young's modulus of the fabric were investigated. Wang [17] built an FE contact model based on the Mindlin-Reissner shell theory to simulate the contact strain and displacement between the body and two sets of garments fabricated of nylon/cotton materials and found that different fabric materials affect the mechanical interaction between the body and garment. Similar research work which used an FE model to analyze the relationship between the fabric material and garment fit was carried out for the leg and sock, and foot and insole [18-20]. However, few studies in the literature have investigated the relationship between bra cup fabric and breast deformation, as well as the contact pressure through numerical simulation.

To address these issues, an FE model is developed based on individual specific geometric shapes and the non-linear mechanical properties of the breasts to simulate the interaction between the breast and bra cup models with different material properties. The simulated shaping effects of the breasts are evaluated by using 4 body measurement items related to the uplifting and gathering of the breasts. The distribution of pressure at the neck and bottom of the breasts due to wearing bras with different cup materials are compared. In order to validate the accuracy of the FE model, the predicted results for breast deformation and contact pressure are also validated with a wear trial. Then, on the basis of the validated FE model, a series of virtual bra fabric materials are inputted into the model to simulate and compare their breast shaping effects. It is anticipated that the FE model could act as a versatile tool for examining the impact of different design parameters, hence facilitating advancements in the bra design and development process.

Experimental

Wear Trial

Subject

A healthy 45-year-old woman was selected as the subject. She is 166 cm in height, and weighs 61.2 kg, with a body mass index of 22.2 kg/m^2. Her bra size is 36C based on the metric sizing system. The project was approved by the University Human Subjects Ethics Committee. Prior to conducting the experiment, informed consent was obtained from the subject.

3D Body Scanning

In order to evaluate the changes in the shape of the breasts after donning bras with different types of bra cup fabrics, a 3D laser body scanner (Vitus, Human Solutions, Germany) was used to capture 3D images of the subject which provided the geometric model for the numerical simulation, as well as the body measurement data. The scanner has a control unit and four sets of moving cameras in columns to capture images of the entire body of the subject with a high resolution of 300 pixels/cm^2. During the scanning process, the subject stood upright with her arms open, placed her feet on pre-marked areas, looked straight ahead and breathed at a

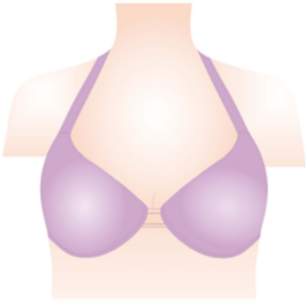


Figure 1. Halter-neck bra.

natural rate.

Bra Samples

A daily use bra with a halter-neck (Figure 1) that is commercially available in the local market was used in the experiment. Two types of fabrics (F1 and F2, single layer) and a fabric-foam laminate (F3) were selected as the bra cup materials. F1 has a rigid woven structure, while F2 has a knitted structure that is highly elastic. F3 is a fabric-foam laminate which consists of PU foam and nylon. The basic physical properties of each type of material are provided in Table 1.

Table 1. Basic physical properties of tested materials

	F1	F2	F3 - Foam	F3 - Fabric
Fabric content	100 % cotton	95 % nylon	Polyurethane	95 % nylon
Fabric structure	Plain weave	Warp knitted	Open-cell	Single jersey
Density	387.4 g/m^2	74.1 g/m^2	108.6 kg/m^3	68.8 g/m^2
Warp (ends/cm)	13.4	14.9	-	20.5
Weft (picks/cm)	18.9	15.7	-	31.5
Thickness (mm)	0.81	0.46	3.62	0.35
Hardness	48	23	19	20

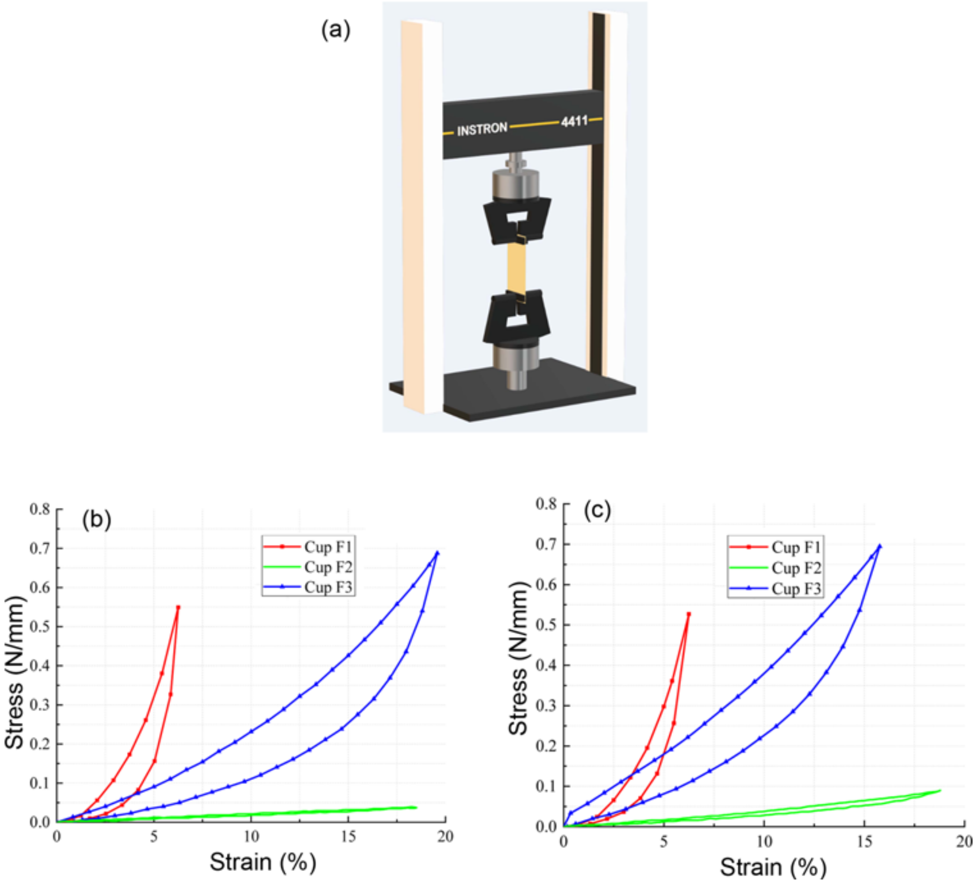
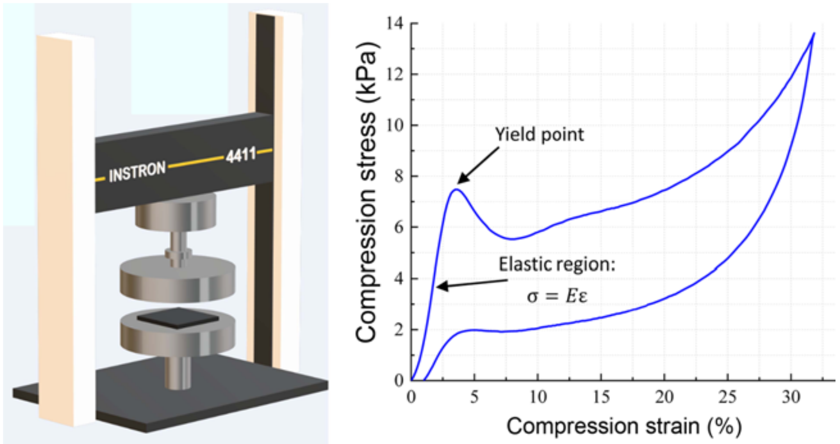


Figure 2. Testing with Instron 4411 tensile strength tester (a) and plotted stress-strain relationship of samples in course direction (b) and wale direction (c).



(a)

(b)

Figure 3. Foam sample tested with Instron 4411 (a) and compression test results for F2 (b).

Determining Mechanical Properties of Bra Samples

Normally, the stretchability of woven or knitted fabric differs in the wale and course directions [21]. The tensile properties of the bra cup fabric in both directions were measured by using an Instron 4411 tensile strength tester (Norwood, MA, USA) (see Figure 2a) according to British Standard BS EN14704-1:2005. The test specimens were cut from the sample bras with dimensions of 50 mm×100 mm. The specimens were mounted between the two grips of the tensile tester which moved at a constant crosshead speed of 100 mm/min and exerted a load onto the edge of the specimens. The corresponding elongation under the external load was recorded to calculate the tensile strength of the fabric. The strain-stress curves plotted from the tensile test results of the three types of bra cup materials in the course and the wale directions are shown in Figure 2b and 2c. For cup F3, the thickness cannot be neglected comparing with in-plane dimensions. Therefore, other than the tensile properties, the compressive modulus should be considered for the moulded cup. A compression test was carried out with the Instron 4411 tensile strength tester for F3 (Figure 3a). The plotted stress and strain are shown in Figure 3b and the compressive modulus can be determined from the slope of the stress-strain curve in the elastic region.

FE Simulation

A commercial FE modeling software, Marc (MSC. Marc 2014.2.0, US), is used in this study to build the FE model and examine the interaction between the breasts and bra with different types of bra cup materials. To reduce calculation time, some assumptions are made for the biomechanical model of the body as follows:

(1) The material properties of the breasts are assumed to be homogeneous and the breasts are a uniform structure.

(2) The torso is regarded to be a rigid surface and the skin and subcutaneous tissues are omitted in the model.

(3) Instead of macro-scaled modeling method which considers the interaction between yarns and fibers [22], the material properties of fabrics modeled in this research are constructed by inputting the constants obtained from material tests.

(4) Friction is neglected in this model.

Geometric Model

i) Sub-model of body

The original model of the body was constructed based on 3D scanned images of the subject without a bra. The 3D images of the upper torso were inputted into Rapidform (Rapidform XOR3, Korea) software. The sub-models of the body included soft tissues of the breasts (Figure 4(a)) and a rigid upper torso (Figure 4(b)). The breasts were removed from the chest with a thickness of 40 mm. The initial generated FE model from the 3D body scans was obtained including the gravity load; however, the simulation should start with a gravity-free model of the body. Therefore, this gravity-free model of the body was acquired by applying gravity upwards on a braless model. The part with the deformable breasts was meshed by using 5 mm tetrahedral elements.

ii) Sub-model of bra

The initial sub-model of the bra was extracted along the outline of the 3D scanned image in which the subject wore the sample bra. The bra has straps, bra cups, a bra band, an underwire and gores (Figure 5). The straps form a halter neck. In this study, the straps, band and underwires were modeled as the shell element in the numerical analysis. Bra cups made of fabrics (F1 and F2) were also modeled as the shell element. Nevertheless, the bra cups made of fabric-foam laminate (F3) in a 3D structure was modeled as a solid

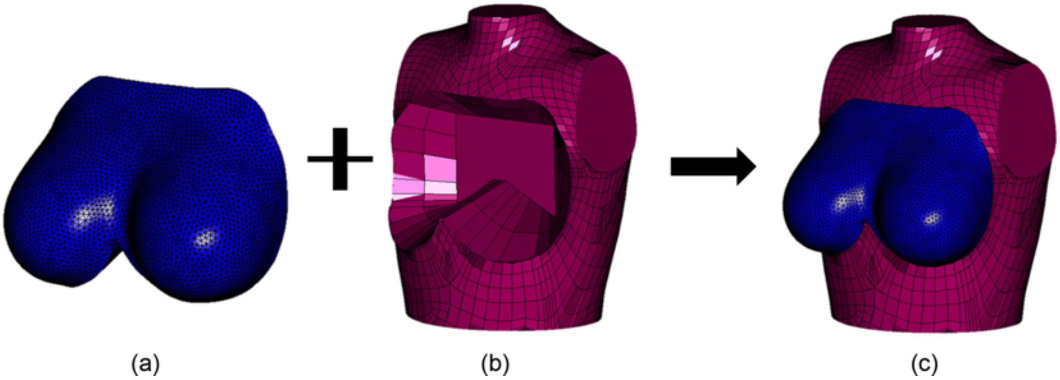


Figure 4. FE sub-model of (a) breasts, (b) rigid torso, and (c) combined body model.

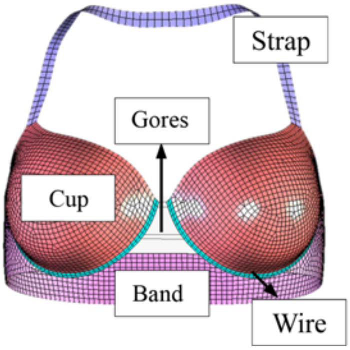


Figure 5. FE sub-model of bra.

Table 2. Coefficients for material parameters in FE sub-model of breasts

Component	Parameter	Value
Breasts	Density (kg/m^3)	1000
	C_{10} (kPa)	0.05
	C_{01} (kPa)	0.052
	C_{11} (kPa)	0.375
	C_{20} (kPa)	0.78
	C_{02} (kPa)	0.63

element which not only underwent in-plane forces but also deformed under compressive forces in the transverse direction. The entire bra was meshed with 5 mm quadrilateral or hexahedral elements.

Material Properties

i) Body

Previously, we carried out a study on the material properties of breasts [23], and generated five Mooney-Rivlin coefficients (C_{10}, C_{01}, C_{11}, C_{20}, and C_{02}) to describe the hyper-elastic characteristics of the breast tissues. The specific details of each coefficient are given in Table 2.

ii) Bra components

To construct the material models of a bra, the bra components need to be modeled with the proper elements and accurate physical properties. The bra straps and the band of the bra samples were taken to be isotropic elastic materials with uniform mechanical properties. The underwire was also considered to be an elastic material with high rigidity. In general, the tensile properties of the bra cup fabric are different in the course and wale directions. Therefore, the type of material used for the bra cups is orthotropic in the warp and weft directions in the plane of the material. In considering the thickness of F3, the compressive modulus represents the mechanical property in the perpendicular

Table 3. Mechanical properties of three types of tested bra cup fabrics and other bra components

Bra component	Young's modulus (MPa)		Shear modulus (MPa)		Poisson ratio		Compression modulus E_3 (MPa)
	Course direction (E_1)	Wale direction (E_2)	G_{12}	G_{21}	ν_1	ν_2	
F1	3.68	4.68	0.24	0.29	0.31	0.25	-
F2	0.18	0.23	0.08	0.09	0.24	0.19	-
F3	1.81	1.19	0.09	0.10	0.21	0.29	0.32
Strap	1.5		0.58		0.29		-
Underwire	210,000		78,900		0.33		-
Gore	210,000		78,900		0.33		-
Wing	0.10		0.04		0.25		-
Bra band	0.90		0.35		0.28		-

Table 4. Contact (interaction) settings between body and bra components

Pair of contact conponents	Contact type	Type of contact body
Breast-torso	Glue	Deformable-rigid
Breast-cup	Touch	Deformable-deformable
Bra strap-torso	Touch	Deformable-rigid
Cup-torso	Touch	Deformable-rigid
Bra band-torso	Touch	Deformable-rigid

direction to the in-plane direction. The specific elements and material properties of each bra component are listed in Table 3.

Boundary Conditions of Wearing a Bra

In our previous document [24], the simulation of bra wear starts with the construction of a contact model with a gravity-free model of the body and stress-free bra model. The gravity-free model of the body can be easily obtained by applying reverse gravity on the breasts. For the sub model of the bra, several steps [25] are required to release the tension from the initial geometric model extracted from the scanned 3D body image and convert the sub-model to a stress-free state. The FE model for contact was constructed on the basis of the separated sub-models with the correct contact (interaction) settings (Table 4).

The steps for simulation by constructing a contact model to set the proper wear boundary conditions are provided in a flowchart in Figure 6.

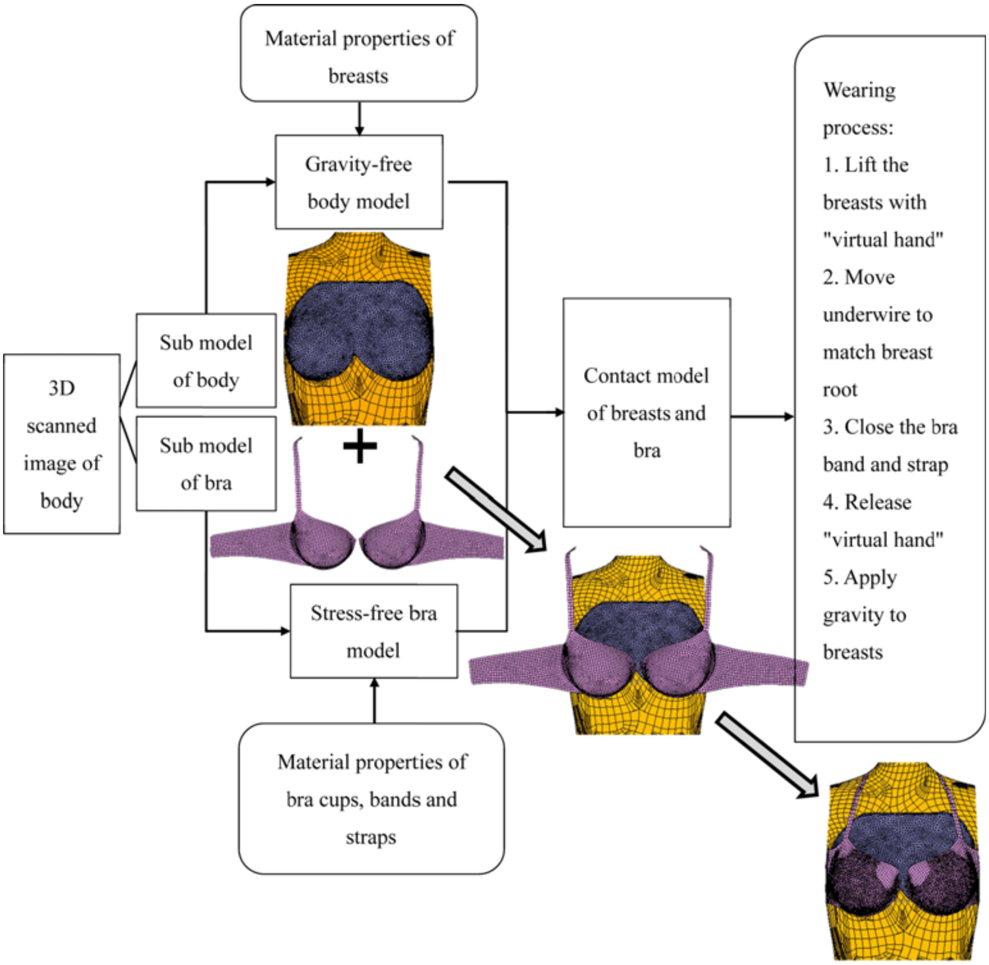


Figure 6. Flowchart of modeling process and boundary conditions.

Results and Discussion

Experimental Validation of FE Model

Deformation of Breasts

In order to validate the FE model, the simulated breast measurements and contact pressure after wearing an underwire bra with three different kinds of bra cup fabrics were compared with the findings in the wear trial experiment. In this study, four measurements related to breast shaping [25] (Figure 7) were used to determine the effects of the uplifting and gathering of the breasts. The descriptions for each item are provided in Table 5. The table also shows the errors between the predicted deformation of the breasts after the subject donned the underwire bras with three different types of bra cup materials. The consistent agreement between the simulated and experimental results indicates that the FE model developed in this study can predict the reshaping of the breasts after wearing different bras with good accuracy and allows bra designers to analyze different bra performances along with fabric material properties.

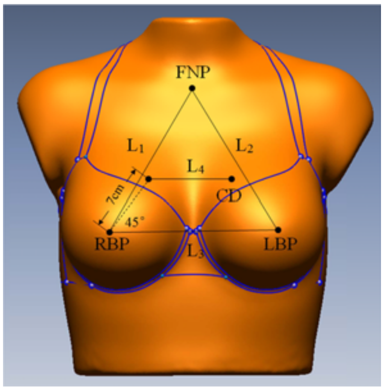


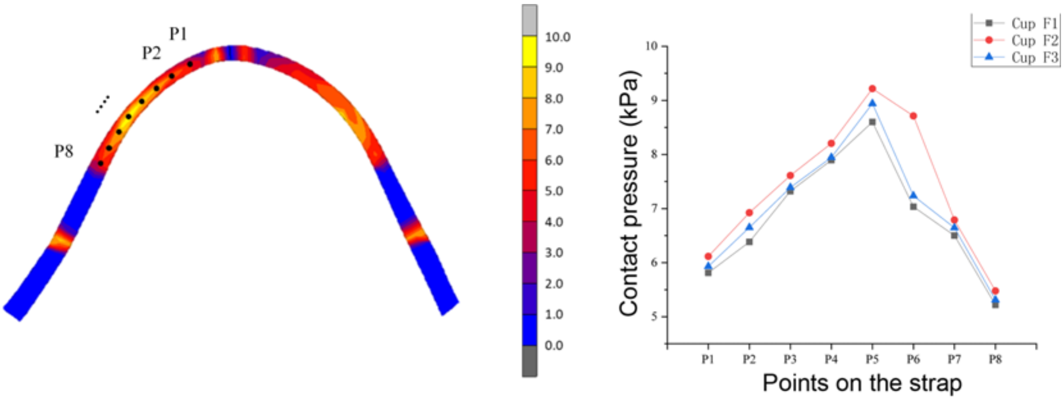
Figure 7. Anthropometric measurements related to shaping of breasts.

Distribution of Bra-breast Pressure

Other than the shaping effect of the bra after it is donned, the amount of contact pressure between the body and bra is also important for evaluating the performance of a bra. In order to determine the distribution of pressure at the neck and bottom of the breasts as those parts can be easily strained or feel pain, the contact pressure calculated from the nodal stresses in the contact region was extracted in the post-processing of the simulation results. The distribution of the pressure along the bra strap was examined by focusing on eight nodes (Figure 8a) around the neck in the contact area. The interval between each node is 1 cm. Figure 8b shows the generated contact pressure after the three bras with different bra cup materials are worn. It can be observed that F2 has

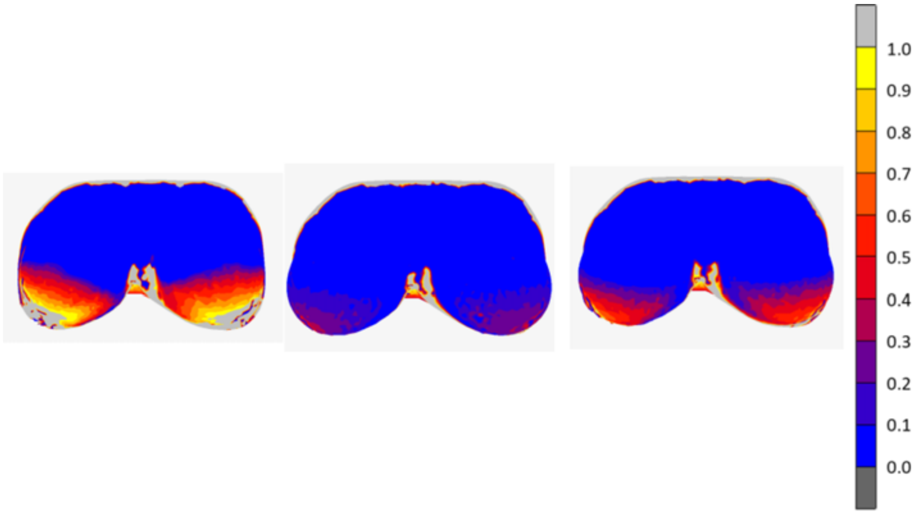
Table 5. Simulated and experimental results of breast measurements (mm)

Item	Breast measurement	Type of cup material	Experiment	Simulation
L_1	Straight line between front of the neck (FNP) to right bust point (RBP) (Examines uplifting of breasts)	F1	208.8	223.1
		F2	232.6	234.1
		F3	218.2	229.9
L_2	Straight line between front of the neck (FNP) to left bust point (LBP) (Examines uplifting of breasts)	F1	210.1	222.3
		F2	232.7	233.8
		F3	220.6	229.5
L_3	Straight line between left bust point (LBP) and right bust point (RBP) (Examines gathering of breasts)	F1	185.2	188.6
		F2	199.2	201.5
		F3	193.7	196.8
L_4	Straight line between two cleavage points (CD) (Indirect means of examining depth of cleavage)	F1	87.5	92.5
		F2	93.1	98.2
		F3	89.5	94.2



(a) (b)

Figure 8. Distribution of pressure on bra strap (a) and simulated results of three types of bra cup fabrics (b).



(a) (b) (c) (d)

Figure 9. Distribution of contact pressure at the bottom of breasts with bra cup F1 (a), F2 (b) and F3 (c) under the contour band of contact pressure (d).

about a 7 % higher peak pressure value on the neck than F1.

As for the distribution of the pressure at the bottom of the breasts, the simulated results of F1, F2 and F3 are provided in Figure 9 as contour plots with similar scales. The averaged values of the contact pressure at the bottom of the breast are extracted from each simulated condition.

Pressure Measurement with Novel Pliance-X System

In order to validate the simulation results, the contact pressure at the position of bra strap and bra bottom were measured by a calibrated Novel Pliance-X system (Novel Electronics, German). A single pressure sensor was used to detect the value of pressure at the position between bra strap and neck and a matrix sensor (2×2 cm) was inserted into the contact area of bottom cup to measure the pressure distribution (Figure 10). To validate with the simulation results at bottom cup, the 4 measured pressure value were taken average to compare with simulation. Table 6 presents the comparison results.

The simulated contact pressure shows the same trend and magnitude as the measured results in the experiment. The highest pressure at the bottom of the breasts was produced by the rigid fabric (F1).

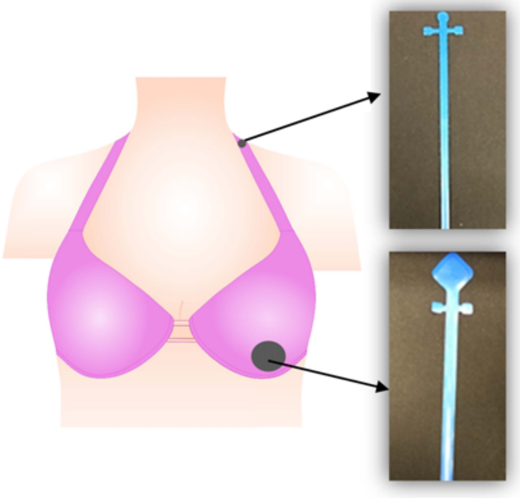


Figure 10. Detected positions and pressure sensors used in pressure test.

Prediction of Breast Deformation and Contact Pressure with the FE Model

The validated FE contact model was then used to simulate

Table 6. Comparison results of measured pressure and simulation

		F1	F2	F3
Pressure generated on neck	Experiment	3.85 kPa	5.12 kPa	4.31 kPa
	Simulation	8.60 kPa	9.21 kPa	8.94 kPa
Pressure generated at bottom breasts	Experiment	1.89 kPa	0.59 kPa	1.16 kPa
	Simulation	2.05 kPa	0.72 kPa	1.23 kPa

bra-wearing conditions by using a series of elastic modulus values of the bra cup fabric in order to provide some basic information on fabric selection for bra designers and manufacturers. Taking into consideration both the bra cup fabric selection process in real life production processes and the convergence problem in numerical simulations (the large discrepancy between the Young's modulus of the breasts and bra cup fabric causes convergence difficulties in non-linear analyses), the Young's modulus of the bra cup was set in the range of 0.5 MPa to 6 MPa at intervals of 0.5 MPa (with a total of 12 conditions). The simulated bra cup fabric was assumed to be an isotropic material. The shaping effects of these bra cups are evaluated by the reduction in the body measurements (ΔL_1 to ΔL_4) when compared with the braless condition. Each set of four breast deformation values based the percentage of displacement of the breasts was correlated with 12 Young's modulus values of any of the bra cup fabrics in the 12 different bra-wear conditions, as shown in Table 7.

Figure 11 shows the deformation of the breasts in terms of the changes in the four body measurements (ΔL_1-ΔL_4) after a bra is virtually worn with different virtual bra cup materials that have different properties. The breast measurements significantly decrease by 1.9 % (ΔL_1) to 4.8 % (ΔL_4) when the Young's modulus of the bra cups increases from 0.5 MPa to 1.5 MPa, but L_1 to L_2 only has an average decrease of 0.1 % for each MPa increase in the Young's modulus from 2 MPa to 6 MPa. It is interesting to observe in Figure 12 that L_3 and L_4 linearly decrease by 0.23 % and 0.39 % on average, respectively, for each MPa increase in the Young's modulus over 2 MPa. This implies that it is more useful to measure the reduction in L_3 (gathering of the breasts) and L_4 (depth of cleavage) rather than the lifting of the breasts (L_1 and L_2) to evaluate the breast deformation produced by a bra.

Table 7. Predicted breast deformation in 12 bra-wear conditions

Young's modulus of bra cup material (MPa)	L_1	L_2	L_3	L_4
0.5	7.1 %	6.3 %	5.7 %	5.7 %
1	7.7 %	6.9 %	5.9 %	6.8 %
1.5	9.1 %	8.7 %	8.9 %	10.5 %
2	9.4 %	8.8 %	9.2 %	11.0 %
2.5	9.4 %	8.8 %	9.3 %	11.4 %
3	9.4 %	8.9 %	9.4 %	11.5 %
3.5	9.5 %	8.9 %	9.5 %	11.7 %
4	9.5 %	9.0 %	9.6 %	11.9 %
4.5	9.6 %	9.1 %	9.7 %	12.0 %
5	9.7 %	9.1 %	9.9 %	12.3 %
5.5	9.7 %	9.2 %	9.9 %	12.4 %
6	9.8 %	9.2 %	10.2 %	12.6 %

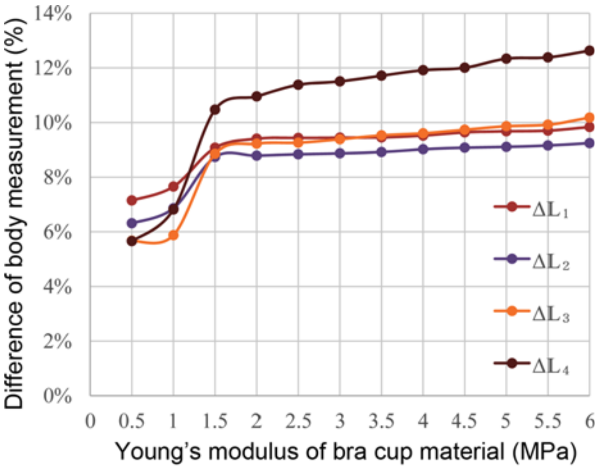


Figure 11. Reduction of body measurements vs. Young's modulus of bra cup fabric.

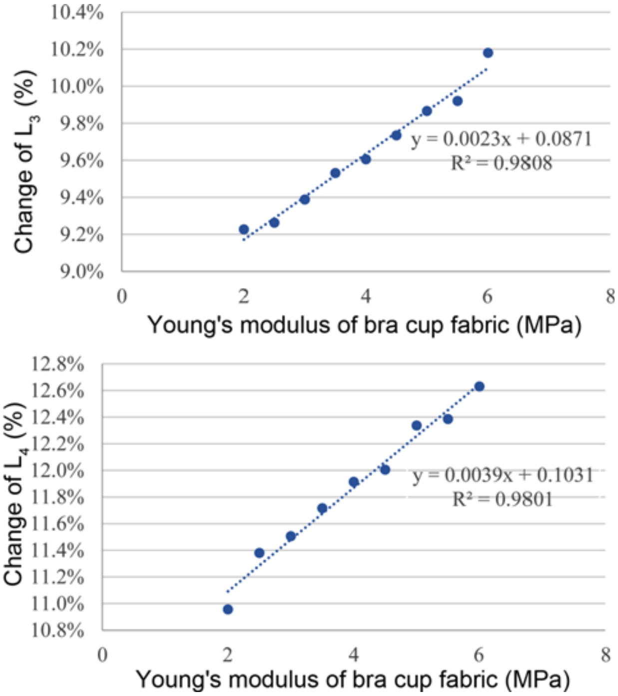


Figure 12. Reduction in L_3 and L_4 with increases in Young's modulus over 2 MPa.

Figure 13 shows the overall shape of the breasts in three conditions: braless and wearing a bra with a Young's modulus of 0.5 MPa and 6 MPa respectively. Compared to the sagging and loose breasts in the braless condition, the breasts are rounder and fuller after a bra is donned especially when a fabric that has a higher Young's modulus (6 MPa) is used.

Rather than conducting an experiment with pressure sensors to obtain point-to-point data which would be difficult to obtain the overall distribution of the pressure, the

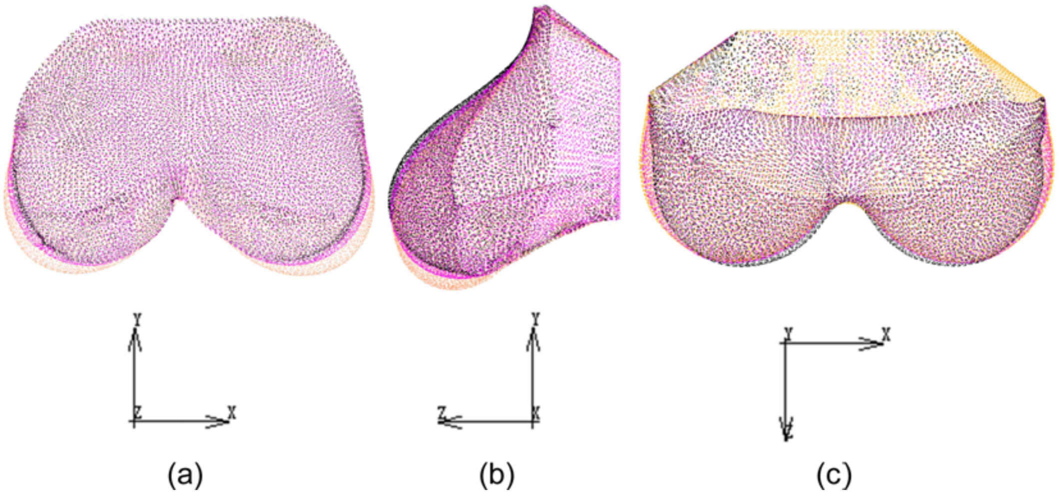


Figure 13. Profiles of breasts in the view of front (a), side (b), and top (c) (yellow denotes braless condition, red is bra cup with Young's modulus of 0.5 MPa and black is bra cup with Young's modulus of 6 MPa).

Table 8. Simulation results of mean contact pressure at bottom of breasts based on 12 wear conditions

Young's modulus of bra cup material (MPa)	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6
Mean contact pressure (kPa)	0.50	0.83	0.96	1.02	1.24	1.25	1.30	1.31	1.32	1.40	1.50	1.57
Standard deviation (kPa)	0.45	0.39	0.59	0.43	0.81	0.52	0.79	0.68	0.60	0.81	0.87	0.68

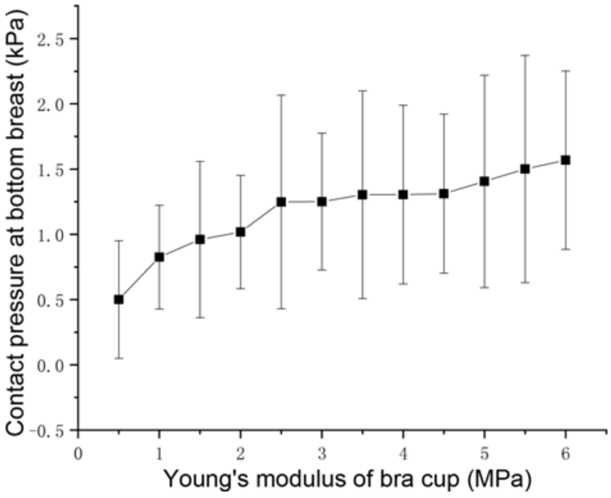


Figure 14. Contact pressure vs. Young's modulus of bra cup at bottom of breasts in 12 wear conditions.

numerical method makes it possible to predict the contact pressure in any area of the body. The mean contact pressure in a selected contact area was calculated by averaging the normal contact stresses on the nodes in the post-processing of the simulation results. The simulation results of the mean contact distribution of the pressure in the areas between the bottom of the breasts and bra cup based on 12 different bra-wearing conditions are provided in Table 8 and Figure 14.

Figure 14 shows that a more stiff bra cup material exerts a higher amount of pressure onto the breasts. The mean pressure for a bra cup with an elastic modulus of 6 MPa (1.57 kPa) is around three times that of a bra cup with an elastic modulus of 0.5 MPa (0.50 kPa).

Effects of Bra Cup Fabric on Breast Shape and Pressure

The results show that a bra cup fabric with a high Young's modulus (high stiffness) has smaller L_1-L_4 values, thus enhancing the shape and position of the breasts in both the vertical (uplifting) and horizontal (gathering) directions. The distribution of pressure generated by the type of bra strap in the halter style bra has a stress hotspot at the intersection of the shoulder and the neck. F2 exerts a higher contact pressure compared to F1 and F3. Okabe and Kurokawa [26] observed a higher contact pressure value in the lower half of the breasts compared to the upper half of the breasts. The simulated results in Figure 7 which show the distribution of pressure at the bottom part of the breasts are in agreement with the results in Okabe and Kurokawa [26]. The bra cup with a rigid material (F1) produces a higher amount of pressure to the bottom of the breasts than that with a lower tensile modulus (F2), while the amount of pressure produced by the bra cup fabricated from PU foam (F3) is between that produced by F1 and F2. Nevertheless, F2 cannot support the weight of the breasts, thus leading to a bra strap with high tension and increased contact pressure around the neck. In contrast, F1 is not affected by the load of the breasts so it is likely to maintain the shape of the breasts with minimum displacement. Although F1 has a better performance in correcting breast ptosis and reducing the pressure hotspot around the neck, this material causes a higher distribution of pressure at the bottom part of the breasts.

The wear trial in this study is limited by its use of only three types of fabrics. In order to overcome the limitation of a small sample of bra fabric for the wear trial, the wear conditions with a series of virtual cup fabrics are simulated. This would provide a wider range of different elastic modulus values from the different types of bra cup fabrics. A potential relationship is subsequently found between the type of bra cup fabric used and interaction between the breasts and bra. The numerical results show that the shape of the breasts changes dramatically when a bra is worn. Even a small elastic modulus (0.5 MPa, with a relatively flexible fabric) of the bra cup material can have a supporting effect on the breasts to a certain degree (right breast is uplifted 6.2 %, left breast 7.3 %, gathering of the breasts increases 5.7 % with a reduction in distance between the two bust points and two cleavage points determined by incremental changes from L_1 to L_4). When the Young's modulus of the bra cup material is increased from 0.5 MPa to 1.5 MPa, an even obvious reshaping of the breasts can be observed. However, the shaping effects of the bra material have little impact when the Young's modulus is between 1.5 MPa and 6 MPa. After the Young's modulus of the bra cup material reaches 2 MPa, the reshaping effect of the breasts in the horizontal direction (L_3 and L_4) is more obvious than in the vertical direction (L_1 and L_2). It can be inferred that it is more useful to measure the gathering of the breasts and depth of the cleavage than the lifting of the breasts to evaluate the amount of breast deformation. The contact pressure at the bottom of the breasts exerted by the different types of bra cup materials (shown in Figure 10) indicates that changes in the material stiffness can produce different levels of contact pressure. Materials with a high elastic modulus are less likely to stretch under the weight of gravity. On the contrary, fabrics with a low elastic modulus are subjected to the forces of gravity and stretched, so that they cannot contain the breasts to a large degree aside from only exerting less contact pressure at the bottom of the breasts. According to previous study [27], the range of the pressure that can be exerted onto the breasts without discomfort is between 0.96-1.355 kPa. Therefore, based on the findings in the literature and the predicted contact pressure in this study, a bra cup material with a Young's modulus that exceeds 4.5 MP will likely exert a pressure at the bottom part of the breasts that is subjectively uncomfortable. After assessing the overall performance of the simulated bra cup materials, the material with a Young's modulus of 1.5 MPa is concluded to be the optimal choice for the current model. This material can provide the breasts with a more aesthetically pleasing shape and lifts the breasts up 8.7-9.1 % more than the other materials, as well as gathers the breasts 8.9 % more than the other fabrics. This material will also not apply an excessive amount of contact pressure (0.96 kPa) onto the breasts. However, this specific value is only applicable to the subject in this research as women with a different breast size and breasts with different degrees of softness have effects on the results of the predicted pressure.

This is a preliminary study that investigates the influence of the material properties of bra cup fabrics on the interaction between the breasts and bra with a numerical FE model. However, the model has some limitations due to the omission of the subcutaneous tissues and skin in the biomechanical model of the body. The predicted pressure by the bra strap is slightly higher than that of the experimental results because of the simplified model. The optimal tensile force of the bra cup fabric is only applicable to the subject-specific model developed in this study. In future work, the model needs to be extended to more subjects who have the same breast size to determine its robustness.

Conclusion

To enhance the bra design process, a biomechanical model based on the FE method is proposed in this paper to simulate the interaction between the breasts and different types of bra cup materials. The deformation of the breasts in relation to the different material properties of the bra cup fabric is simulated and evaluated in terms of the amount of uplifting and gathering of the breasts. The distribution of contact pressure at the neck and bottom of the breasts is obtained after post-processing the simulation results. The errors between the predicted deformation of the breasts and real body measurements from a wear trial are within 6.8 %. The simulated results of both the deformation and contact pressure of the three bras with different bra cup materials show consistent trends with the wear trial. Therefore, the developed numerical model can be used to evaluate the overall shape of the breasts after wearing different bras with reasonable accuracy. Amongst the 3 types of bra cup materials studied, F1 which is a rigid material provides better breast shaping effects based on both the amount of uplifting and gathering of the breasts but applies a higher contact pressure at the bottom of the breasts. Although F2 which is a soft and flexible material can reduce the contact pressure at the bottom of the breasts, it does not provide adequate support and causes a pressure hotspot at the intersection of the shoulders and neck. The proposed model shows that bra cup material is a key parameter in bra design for improving the shaping of the breasts through a higher Young's modulus value of the bra cup fabric. However, the uplifting and gathering of the breasts are not further enhanced after the elastic modulus exceeds 1.5 MPa. To evaluate the shaping effect and minimize the contact pressure, a bra cup fabric with a Young's modulus of 1.5 MPa is considered to be the optimal material for the subject in this study.

The breast and bra cup models with different material properties in this study provide a quantitative description of the complex interactive process between the breasts and stretchable fabric. The results can provide the basis for bra designers to select the appropriate bra cup material in the early stages of bra design which would provide better breast support as well as an acceptable level of contact pressure. In future work, the model of the body can be built with subcutaneous tissues and skin which have been omitted in this study, and predict the distribution of pressure in the neck area more accurately. More mechanical properties of the bra cup fabric (such as the compression modulus of the foam cup, thickness, etc.) or other design factors (such as shape of the bra cup and underwire, tension of the bra strap, etc.) can be tested as the variables that affect the interaction between the breasts and bra.

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