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Title page

3D bra and human interactive modelling using Finite Element Method for bra design

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Abstract

Bra design experiences a long process of development including some key aspects like material selection, pattern making and grading. The design and development processes are highly complex, which consist of many pattern engineering stages, specialized technologies and multiple trial-and-errors. It is anticipated that a 3D bra design that incorporates information on the interaction between bra and breast can effectively improve the design process for optimal fit and comfort. In this paper, a novel personalized modeling system based on finite element (FE) contact model is first presented to simulate the breast-shaping effect and the pressure distribution of the skin exerted by a bra. The new knowledge can provide a basis for the computer-aided-design of well-fitting bras for the target customers. The FE body sub-models include a rigid torso and two soft breasts wearing a bra with or without an underwire. The geometry of the body was based on the 3D-scan data and the property of the breasts was considered a hyper-elastic Mooney-Rivlin model for simulating the deformation of the breasts. The simulation of bra wearing was performed by an FE contact model in a user-defined coordinate system. There were two main steps: 1) closing the shoulder straps and bra underband at the center back of the body, and 2) adjusting bra position using "virtual hands". The simulation results showed that although the wireless bra exerted less pressure on the breast, the shaping effects in terms of lifting, gathering and protruding were more obvious in the underwired bra. This result is consistent with the actual bra-wearing. The effect of wireless bra on the breast deformation was three fifths of the effect of underwired bra and this relationship could be used to predict the deformation of breasts with different materials of underwire at the early stage of bra design. The relative errors between simulated results in terms of the breast deformation and pressure distribution with a fitting experiment on an underwire bra were less than 10%. The FE model developed in this study, therefore, can be used as fundamentals for various sensitivity analyses about different bra design features for predicting the deformation of the breast shapes and comfort pressure with reasonable accuracy.

Keywords: Finite element method, breasts, shaping effect, pressure

1. Introduction

Traditional bra design is a tedious process involving developing design prototype, pattern making and fabric selection. Improper construction technique and/or fabric choice in any of the bra design processes will fail to satisfy the need of customers and longer the development cycle [1]. In the loop of pattern making and fabric selection, it is the most time-consuming part which involving many trial-and-errors and material preparations. It highly relies on the expertise of the bra designers who having the concept of how the human body will react to the design features and also have a thorough understanding of fabric performance to develop a good bra [1]. Therefore, in order to set up a platform or system to let the customer feel different design features visually and digitally, as well as providing the bra designer basic information of interaction between bra and human body, computer simulation has become a potential new tool to address those problems. It can assist the bra manufacture to design individual bra fit with optimized supportive shape and comfortable pressure. Computer-aided-design (CAD) allows easy modification of design parameters to fit a virtual model for a quick evaluation of appearance [2]. 3D virtual garment simulation can shorten the clothing design process by virtual wear, fitting evaluation and pattern alteration [3,4]. Some commercial solutions such as Browzwear, Clo3D and OptiTex allow to create the virtual fit process by inputting the 2D pattern data and fit on a 3D digital human model (avatars) to evaluate the garment design [5]. Meng et al. [4] proposed a virtual try-on system based on CAD to easily alter or edit the pattern in both 2D and 3D manners according to different shapes of body. Li et al. [6] generated the garment prototypes from individual human models and alter the garment by local parameterization. These technologies make it easy to obtain the deformation of garment (stretching or draping) and distance ease between garment and human body. However, because the avatars used in these methods are rigid, it fails to give the information of contact pressure distribution and shaping change of soft tissues during wearing process. Parametric optimization [7] based on finite element (FE) modelling has also been used in garment design without making the real prototypes [8], wasting the fabric, and the time for fitting [9,10]. In addition, comparing with the 3D virtual garment simulation technique, FE simulation allows a customer-specific model combining with real detailed information of the customer and analyzing the individual response in terms of body reshaping and comfort pressure while fitting on different garments.

Previous research has focused on the interaction between the human body and clothing in terms of the deformation of fabric and pressure distribution on the body, so as to improve the performance of garments [11]. Zhang et al. [12] developed an FE contact model between a foot and a sock to predict the stress and pressure distributions under a cotton sock and a Nylon sock. Dan et al. [13] also used an FE model to investigate the relationship between pressure and displacement at the top part of socks. Franciosa et al. [14] built a parametric FE model of footwear to simulate the pressure on the plantar surface contacting with the shoe sole. Zhang et al. [15] first developed a numerical model of a virtual body and a simplified garment by using the FE method to simulate dynamic contact pressure and deformation of garments, but that was an artificial rigid body.

Previous studies mainly investigated the pressure distribution based on a biomechanical model with the garment already worn under dynamic load [16] or gravity load [17] but neglected the actual wearing process. Ishimaru et al. [18] divided the T-shirt into several parts and simulated the process of wearing and predicted the large deformation and pressure distribution. However, they considered the human body to be non-deformable and used a rigid mannequin to validate the simulation results.

The application of FEMs in designing bra fit is still in its infancy because of the highly complex non-linear problems that involve the irregularities of the breast geometry, hyper-elastic material properties of soft breast tissues, and contact mechanics between a bra and soft breast tissues. However, it will be a breakthrough in the intimate apparel industry if FE method can be successfully applied to simulate the real process of bra wearing. The most critical part of an interaction analysis is to build an accurate FE biomechanical sub-model of the breasts with the appropriate material properties to observe the deformation or movement under external load. Chen et al. [19] used hyperelastic neo-Hookean material to simulate the large deformations in the breasts during three activities (walking, stepping and running) and validated the results with motion capture experimental data. However, few in the literature have reported analysis on the interaction between the breasts and a bra. Bel-Brunon [8] built a numerical model for a bra and investigated its effects on breasts during exercise. They added an FE contact model with motion boundary conditions that were the same as those in an experiment and obtained the simulated results of the stresses and strains induced onto the breasts. To validate the FEM model, the displacements of the nipple position were compared with experimental data. Li et al. [17] also developed and validated a model to simulate the dynamic interaction between a sports bra and a rigid body with elastic breasts during breast falling and bouncing motions. However, as the bra fabric underwent stretching to fit the soft breast, the pre-tension of the bra during wearing cannot be neglected. This pre-tension affecting the interaction between human body and bra was not mentioned in previous study.

Recently, FE-based machine learning has been proposed to predict the mechanical behavior of breast tissues [20], but it is challenging to predict the real-time breast shape and contact pressure under the bra of different design parameters such as fabric, pattern, shape of underwire [21]. A reliable FE contact model to simulate the entire bra wearing process is essential before building such a machine learning model. The purpose of this study was to develop FE contact models of the hyper-elastic breasts and underwire bras to simulate the bra wearing process by applying realistic boundary conditions and numerical algorithm. The outline of the bra prototype was directly extracted from the subject's body scan. The breast deformation and the skin contact pressure can be obtained through the numerical simulation simultaneously. A newly created bra with different design features, such as material properties of fabric, tension of strap or band, bra types with or without underwire, can be obtained easily by altering the parametric based on the initial bra prototypes. In this paper, the shaping effect of the bra and pressure distribution of the breasts was predicted for the initial prototype of underwired bra and a wireless bra by editing local parameterization. The results were compared and validated with corresponding experimental data.

The rest of the paper is organized as follows. Section 2 shows how an FE contact model of the breasts and a bra were constructed with suitable boundary conditions applied. The entire process of bra-wearing was simulated to predict the deformation of the breasts and skin pressure. In Section 3, the simulated results were validated with the findings of the fitting experiment. In Section 4, the wearing results of an underwire bra and wireless bra were discussed with limitations acknowledged and recommendations proposed. Finally, Section 5 summarizes the study and draws the conclusions.

2. Material and methods

Fig.1 outlines the methods proposed in this study. The experiments contain five parts: a) 3D body scan for building the geometric models of the body and the bra, b) fabric test for obtaining the material parameters, c) motion capture for determining the breast material properties and d) pressure test for validation of the simulation results and e) bra fitting for measuring the breast-shaping effects quantitatively.

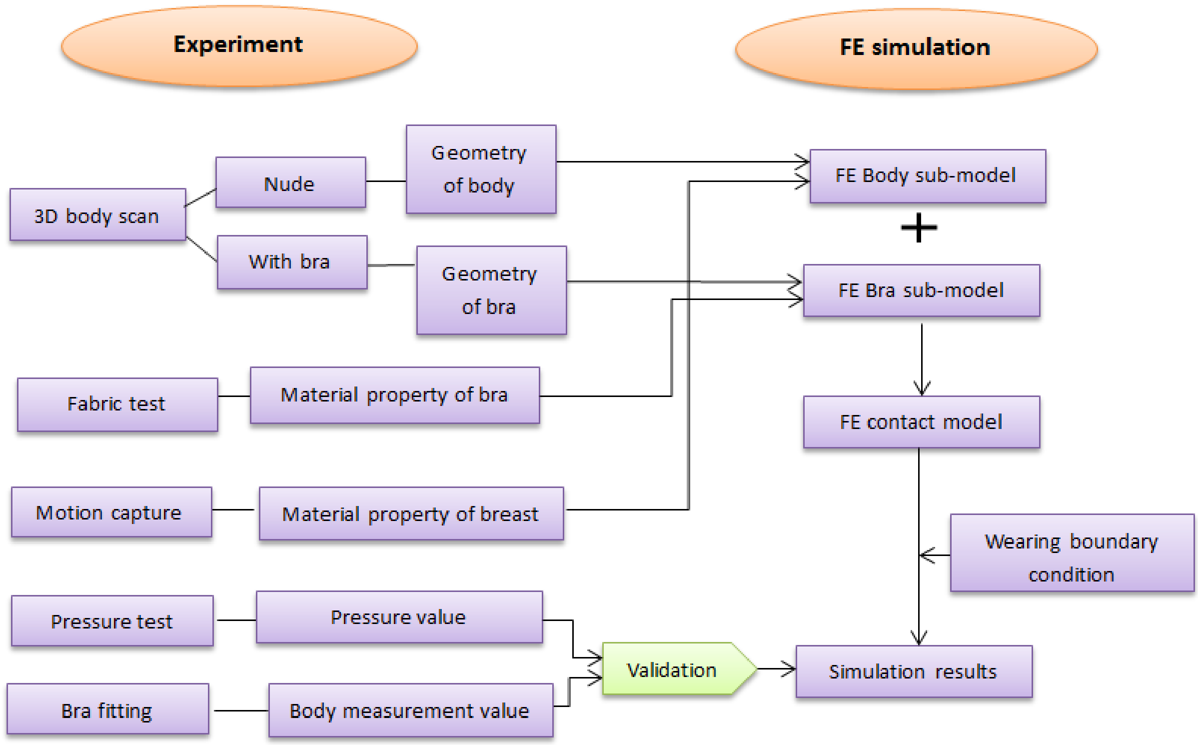


Fig. 1. Experiments and FE simulation

2.1 Experiments

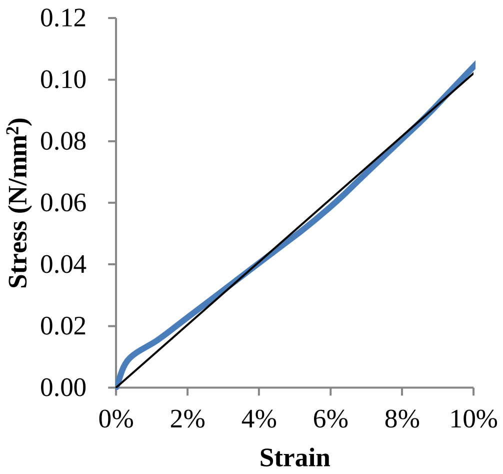
2.1.1 3D body scanning

In order to acquire the breast shape for the fitting experiment, a 3D laser body scanner (Vitus, Human Solutions, Germany) was used to capture the body surface of the subject in three different wearing conditions– no bra, single-layer underwired bra and padded underwired bra. As it is difficult to find the breast roots in nude, the subject was asked to wear a single-layer underwired bra to gently lift her breasts.

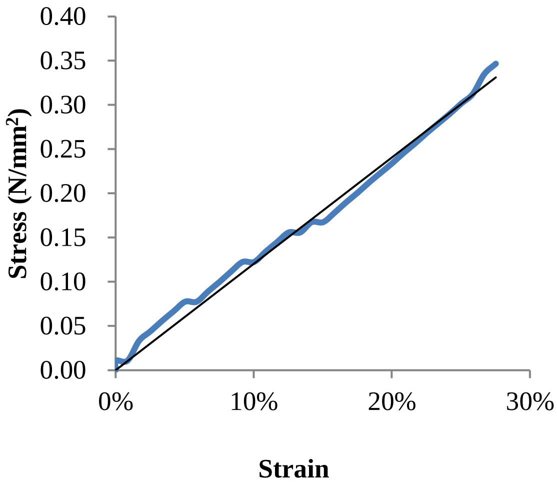
The subject was a healthy woman with a height of 166 cm, weight of 61.2 kg, and body mass index of 22.2 kg/m^2. Her bra size was 36C in the Metric system. The project was approved by the University Human Subjects Ethics Committee. Before the experiment, informed consent was obtained from the subject.

2.1.2 Fabric Test

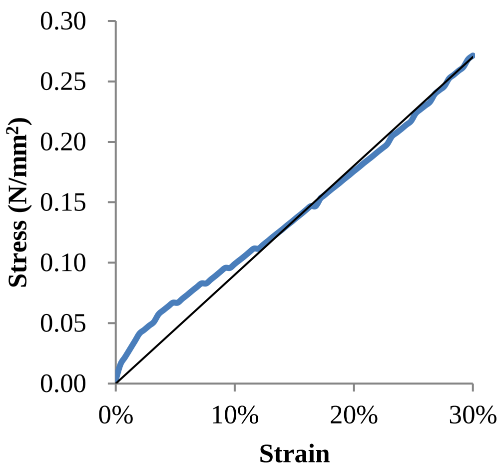
The fabric elasticity of each bra component was measured using an Instron tensile tester system (Norwood, MA, USA). In this study, the material model for the bra component was assumed to be the isotropic elastic material type with uniform tensile property in both directions. Based on the industrial practice in pattern design and development being adopted in most tight-fitting apparel, the bra band at rest is slightly deducted from the underbust circumference of the target customer, corresponding to the elasticity of materials. Hence, when the bra is worn, it can fit securely and comfortably on a woman's body. The reduction percentage ranges from 15% (for stiff material) to 25% (for stretchy material) for design of bra band [22]. Therefore, the elastic modulus of the bra band at 20% strain was used in the FE model. For the bra cup, the fabric cut-piece is made about 5% smaller than the "across cup" (the horizontal curve line passing through the nipple, so that it can prevent the breasts from spreading outward [23]. The shoulder straps need to adjust to ensure secure support for various mass of breast. The elongation for the shoulder strap is usually around 10% [24]. The Young's Modulus of these bra components can be calculated at these strain points and input into the FE bra sub-model as material parameters. The strain-stress curves in the tensile test for the bra shoulder band, cup and strap were shown in Fig.2.



(a) Strain-stress curve of bra cup



(b) Strain-stress curve of bra shoulder strap



(c) Strain-stress curve of bra band

Fig. 2. Strain-stress curves of bra components in the tensile test

2.1.3 Motion Capture

A motion capture experiment was necessary to capture the deformation of breasts when wearing a bra. The methods of motion capture have been explained in our previous work [25].

2.1.4 Pressure test

The skin pressure (shown in Fig.3) under the cup (P_1, P_2, P_3 and P_4), bra band (P_5) and shoulder strap (P_5) was measured by using a calibrated Novel Pliance-X system (Novel Electronics, Germany). A 2*2cm matrix pressure sensor was used for testing the pressure under the cup because it requires a larger area of sensor to detect the small pressure on a soft breast. The pressure of the elastic band and shoulder strap was measured by a single pressure sensor.

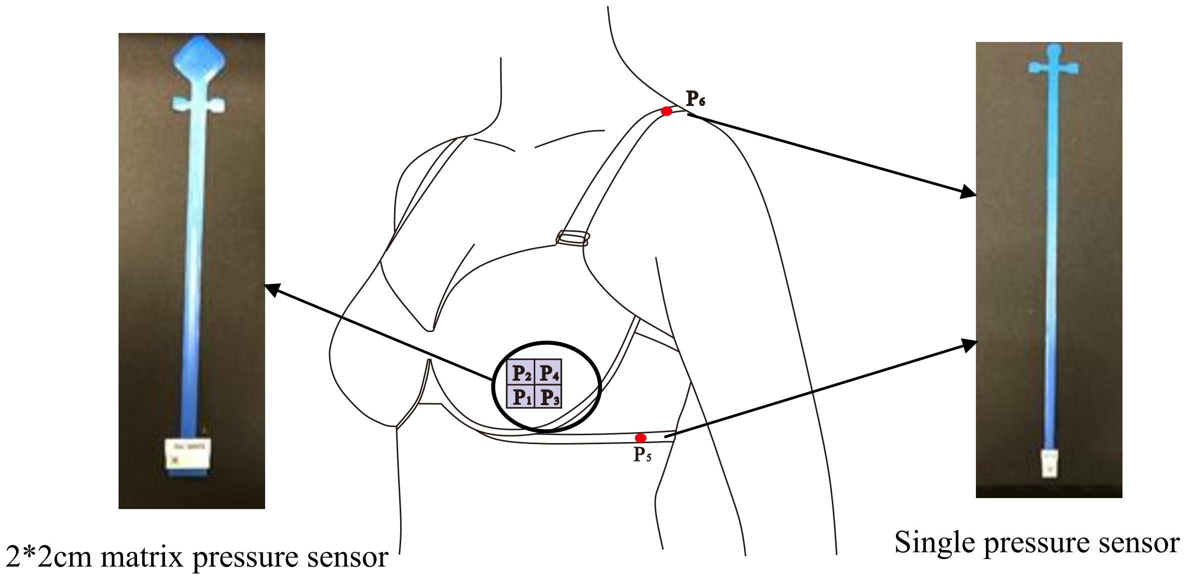
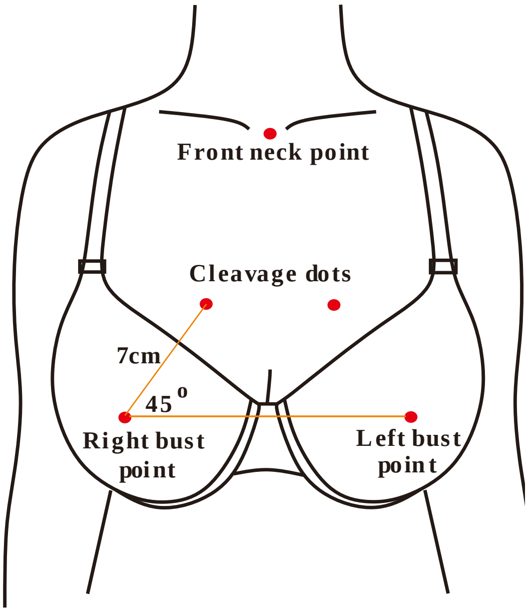


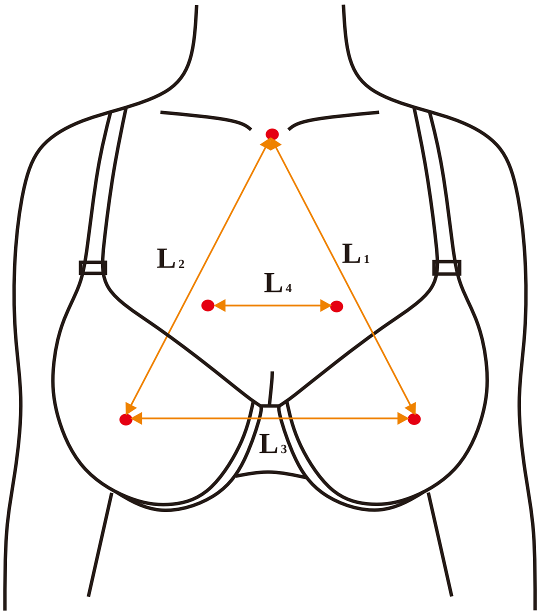
Fig. 3. Points measured for testing pressure

2.1.5 Bra fitting

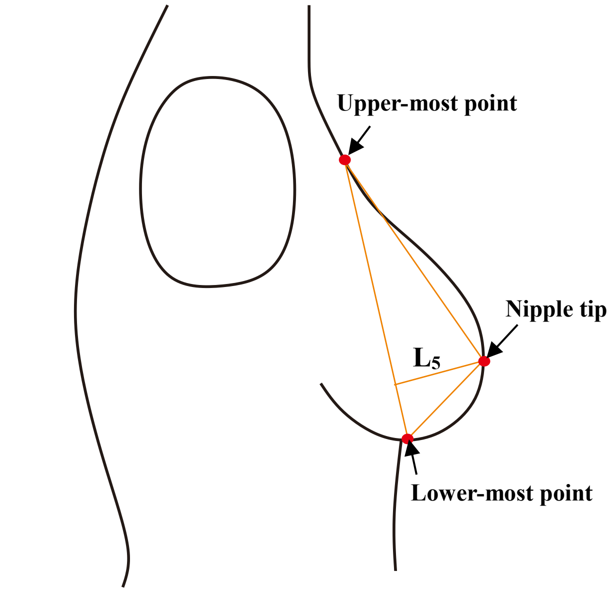
In the fitting experiment, four reference points - front neck point, cleavage dots, left nipple and right nipple (Fig 4a) were marked on the body of the subject to quantify the change in breast shape based on four reference lines (Fig. 4b) – L_1 from the front neck point to the right nipple; L_2 from front neck point to the left nipple; L_3 from the right to the left nipples; and L_4 between the cleavage dots. The lifting and gathering effects of the breasts are measured in terms of the incremental changes ΔL_i. The breast shape on the vertical direction and cross-sectional planes are also evaluated by using the Rapidform XOR3 software (INUS Technology Inc., Korea) (Fig.4c). Three reference points (upper-most point, nipple and lower-most point) form a triangle on a vertical plane with a measure of “breast projection” L_5. Another group of three reference points (outermost, nipple and inner-most points) form another triangle on a cross-sectional plane with a measure of “breast depth” L_6 [26].



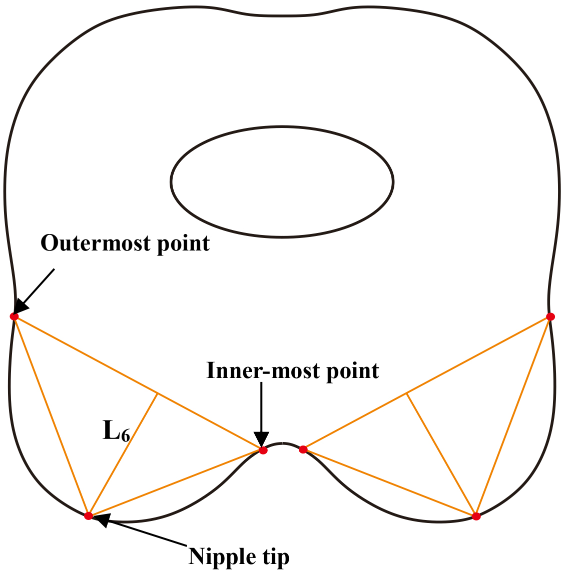
(a) Reference points marked on body



(b) Body measurements: front view



(c) Breast projection L_5 defined on a vertical plane



(d) Breast depth L_6 defined on a horizontal plane

Fig. 4. Reference markers and reference lines on the body

2.2 FE simulation

Fig.5 shows the FE simulation that contains two main parts. First is to utilize the geometric body figure and the material properties to construct a body-bra contact model. Second is to set proper boundary conditions to realize the simulated bra-wearing process.

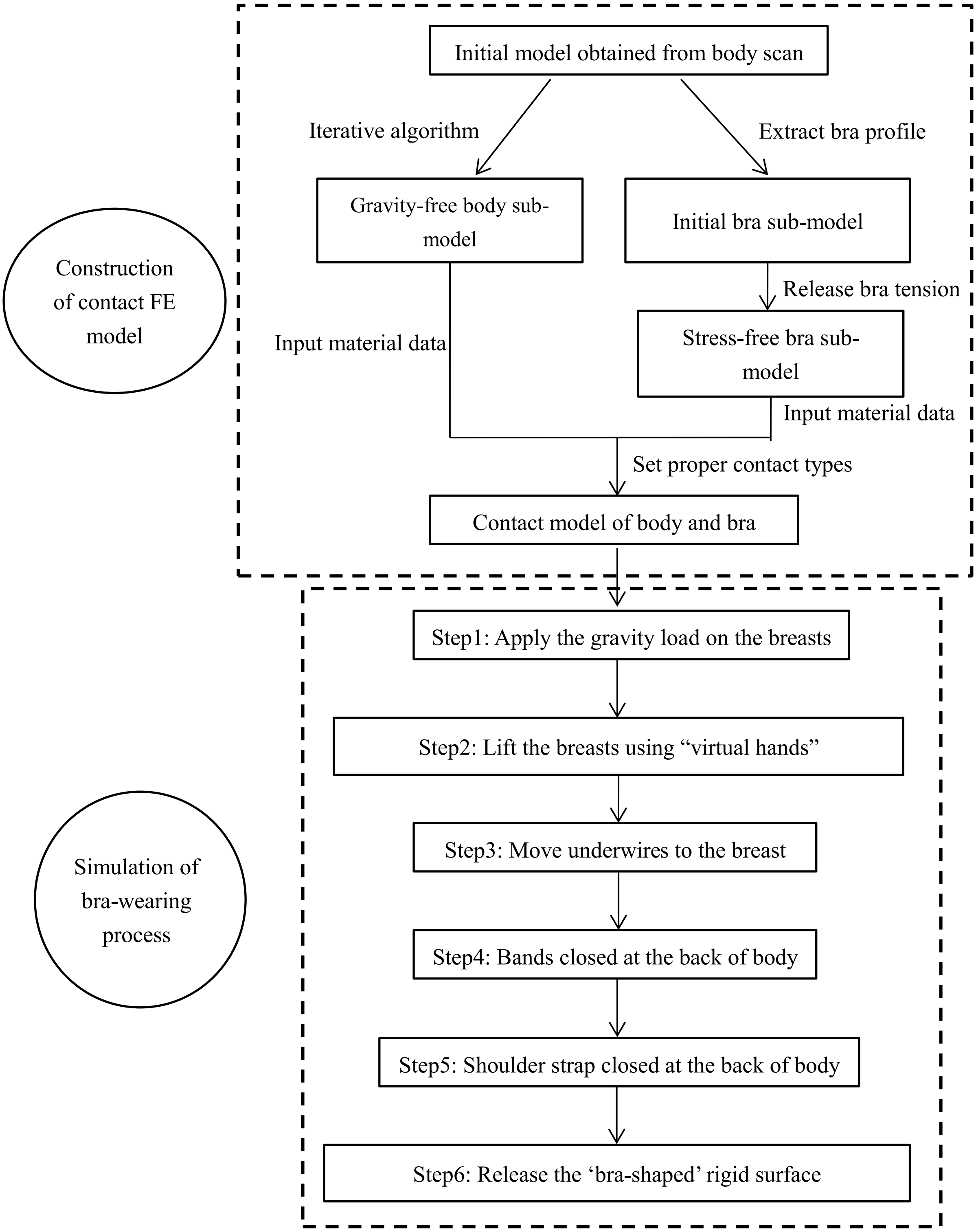


Fig. 5. Construction of FE contact model and simulation process

2.2.1 Construction of FE contact model

i) FE body sub-model

The FE model of the body included a rigid upper torso and two soft breasts (Fig. 7a). The initial geometric model of the upper torso was obtained from the scanned image of the live subject wearing the soft-support underwired bra. Using Rapidform software, the breasts were extracted from the body with a thickness of 40 mm and meshed by 5 mm tetrahedral elements.

As the bra has slightly deformed the breast shape, an external load was applied by using a FEM software Marc (MSC Marc 2014.2.0, US) until the nipples matched with the corresponding coordinates as in the braless image. This FE body sub-model (M_0) had both the correct breast root and unsupported breast shape. In order to simulate the effects of gravity and contact forces, the next step was to obtain a stress-free body model as the starting geometric configuration before FE simulation of wearing the bra. The unloaded body sub-model was calculated by an inverse algorithm (shown in Fig. 6.) proposed by Eder et al. [27]. The initial configuration of gravity-free body model was obtained by applying an upward gravity on the braless model M_0. Nevertheless, this geometric model cannot be used as the starting state of simulation because the hyper-elastic material type of breast tissue shows nonlinear behavior when subjected to large deformation. The validation model was generated after applying the gravity on the initial configuration of gravity-free model. After comparing the validation model with the real deformed model M_0, the difference of configuration between the two models can be adjusted by an external force which will be derived from this step and loaded on the Initial configuration of gravity-free model to recalculate the shape of breast after apply the gravity. The iterative loop will be ended if the difference of the two consecutive iterative models is less than 5% at the first iterative configuration.

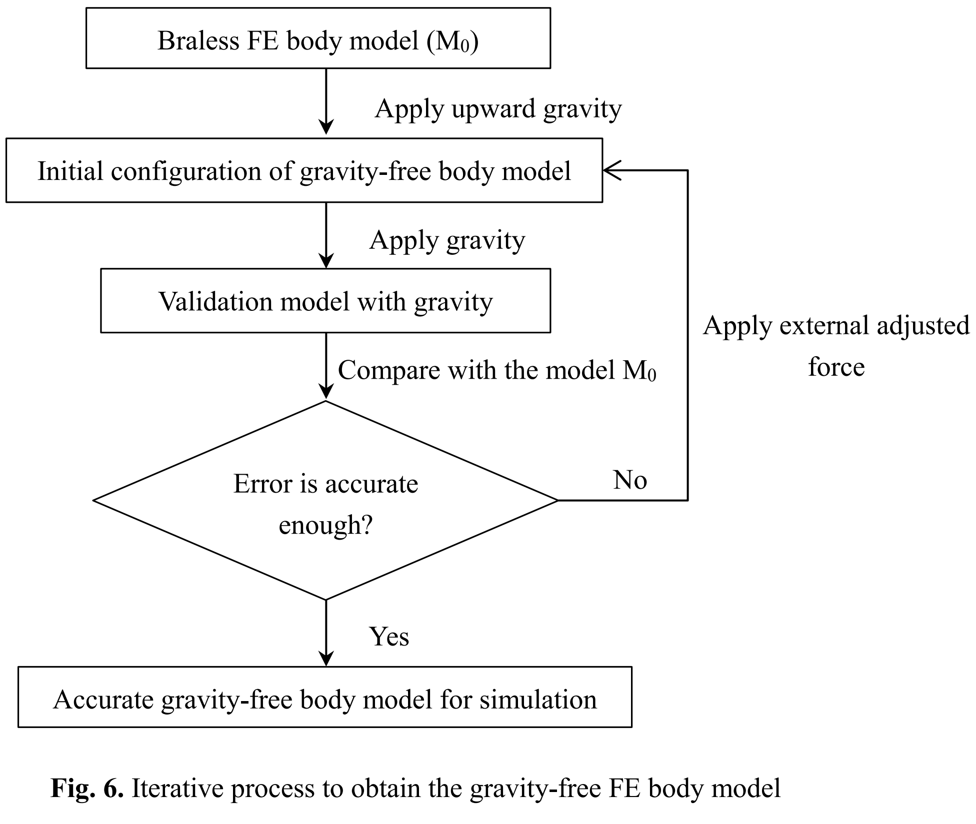
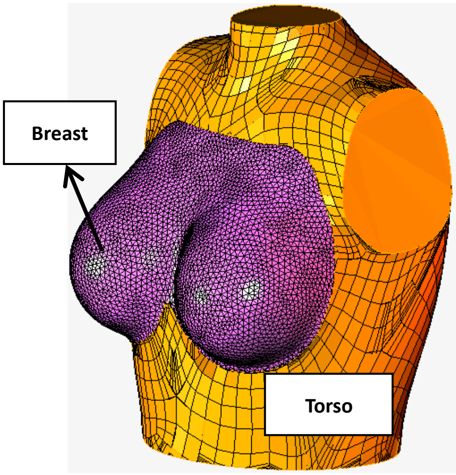


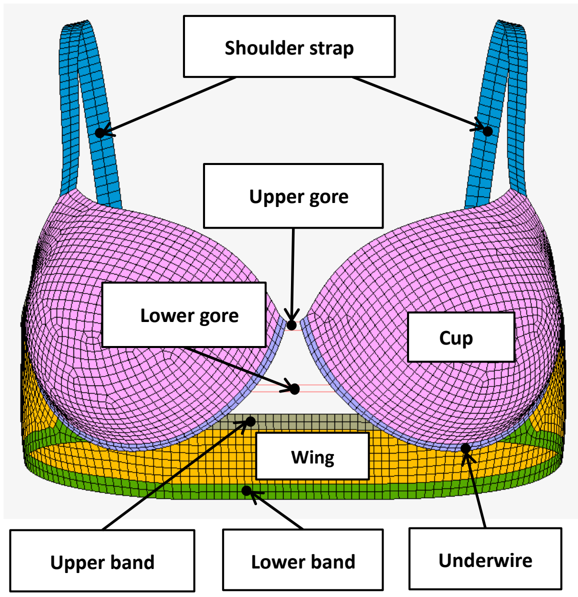
Fig. 6. Iterative process to obtain the gravity-free FE body model

ii) FE bra sub-model

A relaxed bra cannot stand by itself for 3D scanning. Therefore, the initial geometric bra sub-model was extracted based on the outline of bra cups in the scanned image of supported breasts. The bra sub-model has a pair of bra cups with shoulder straps and underwires, upper & lower gore, and a wing sewn with elastic upper & lower bands. The entire bra was meshed by 5 mm quadrilateral elements (Fig. 7b). The bottom of the cup and the underwire share the same nodes in the bra sub-model.



(a) FE mesh model of the human body



(b) FE mesh model of the bra

Fig. 7. FE mesh models of human body and bra

2.2.2 Material parameters

i) Body material

The breasts were considered hyper-elastic and subject to large deformation. The strain energy density function W can be written as:

$$W(I_1, I_2) = \sum_{i,j=0}^{2} C_{ij}(I_1 - 3)^i (I_2 - 3)^j \tag{1}$$

where Cij represents the hyperelastic parameters that characterize the nonlinear elastic behavior of the breast material [28] and I_2 are the first and the second invariants of the components of the left Cauchy-Green deformation tensor B, in the forms of:

$$I_1 = tr(B)$$

$$I_2 = \frac{1}{2}[(tr(B))^2 - tr(B^2)] \tag{2}$$

where tr means the trace of a matrix. $B = F \cdot F^T$, where F is a deformation gradient, F^T is the transposition of F.

In this study, n was assumed to be 2 for the breast material regarded as Mooney-Rivlin. It was characterized by five coefficients (C_{10}, C_{01}, C_{11}, C_{20}, and C_{02}) to present their nonlinear behavior. According to our previous research, the material coefficients of the subject's breasts are listed in Table 1 [25].

Table 1

Coefficients for material parameters in the FE breast sub-model

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

ii) Bra material

The fabric mechanical properties of the bra sample used in the fitting experiment were measured by using an Instron 4411 tensile strength tester (Instron, High Wycombe, UK). The elastic moduli values were recorded at an appropriate extension within the linear region of the stress-strain curve. Table 2 shows the mechanical parameters of each bra component.

Table 2

Mechanical properties of bra components applied in the FE bra sub-model

Component	Material model	Young's modulus (MPa)	Poisson's ratio	Type of element
Shoulder strap	Elastic	1.2	0.3	Shell
Cup	Elastic	1	0.3	Shell
Gore	Elastic	210000	0.3	Beam
Underwire	Elastic	210000	0.3	Shell
Wing	Elastic	0.1	0.3	Shell
Band	Elastic	0.9	0.3	Shell

2.3 FE Contact model

There are three contacting bodies in the FE contact model - a rigid torso, two deformable breasts and a bra. The type of contacts was mainly "touch". For the contact between the breasts and the torso, it was "glue" that means no relative sliding in the contact area. During the bra wearing process, the shoulder straps and band will be stretched from the relaxed length and come into contact with the rigid torso, only the cups will interact with the breasts. The contact pairs are listed in Table 3.

Table 3

Contact modelling of breast and bra

Contact pairs	Contact type	Type of contact body
Breast-Torso	Glue	Deformable-Rigid
Breast-Cup	Touch	Deformable-Deformable
Shoulder strap-Torso	Touch	Deformable- Rigid
Cup-Torso	Touch	Deformable- Rigid
Band-Torso	Touch	Deformable- Rigid

2.4 Simulation of bra wearing process

When a woman is wearing a bra, the underwire must correctly sit on the breast roots. The bra cups and band are stretched to fit the body with appropriate tension, but this causes breast deformation and exerts pressure onto the skin. The force of the fabric recovery that is acting on the breasts which are induced by fabric tension should equilibrate the gravity to reach a static equilibrium. However, it is challenging to analyze the mechanical body-bra interaction in such a 3D stress condition.

In the real life, the process of wearing a bra (Fig. 8) includes the following three steps.

a) The underwire rotates from point B to B' against the breast root at the center front (point A) of the body.
b) The band wrapping around the chest wall and stretching from its relaxed length to fit the under bust.
c) The back end of the underwire tip (point B' in Fig. 8b) springs open to the point B'' to fit the curve of the breast root.

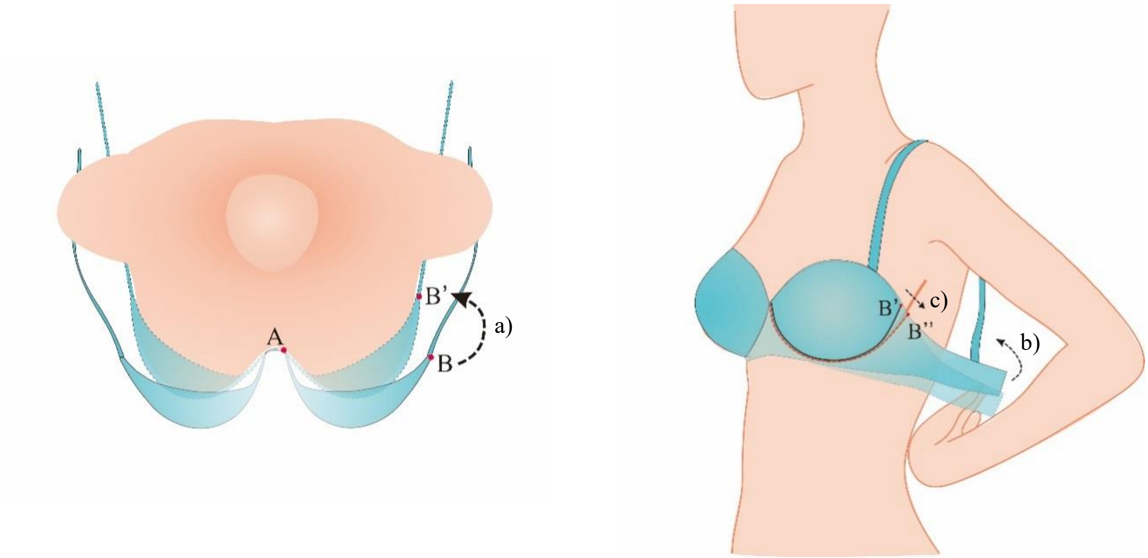


Fig. 8. The process of wearing a bra in real situation

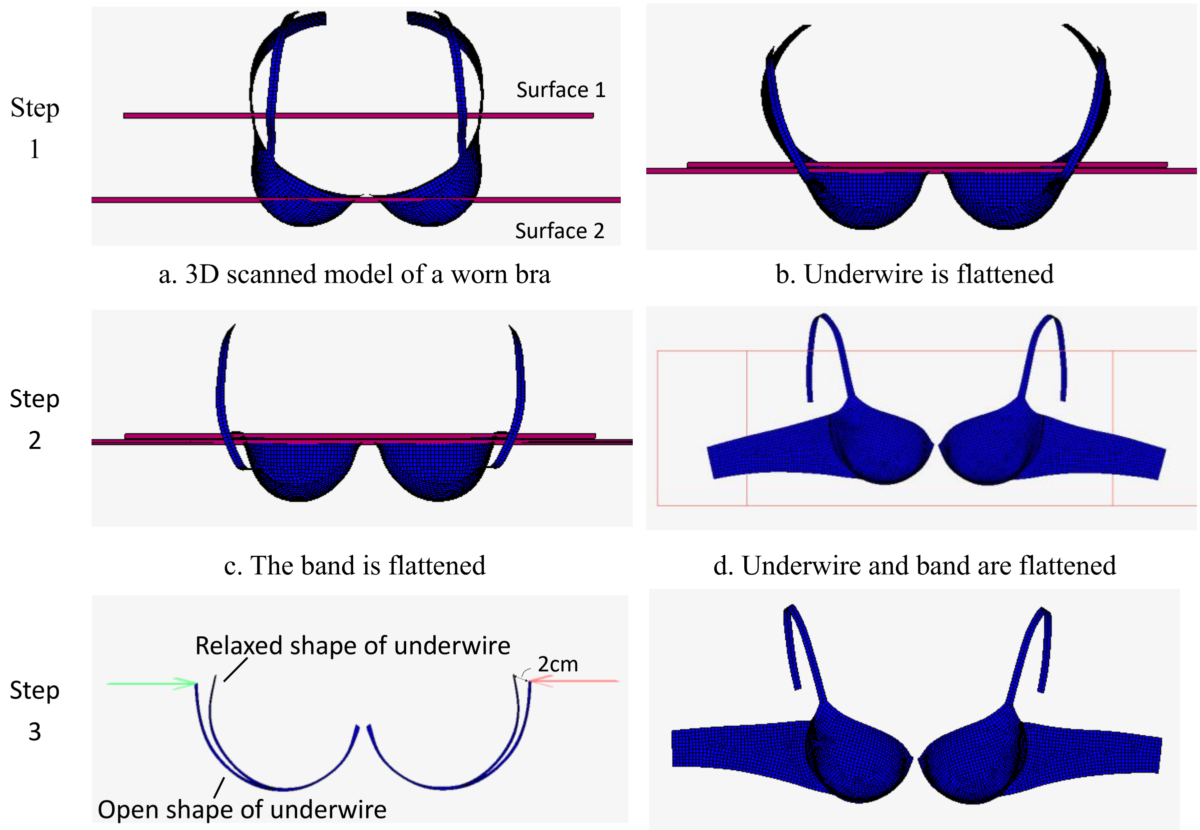
2.4.1 Stress-free bra sub-model

To simulate the interactive force between the body and a bra, it needs a gravity-free body sub-model and a stress-free bra sub-model (i.e. with relaxed shoulder strap, band and underwire in a 2D format). In the tension release stage, the shoulder strap and band should be relaxed and in its initial length in a 2D plane, while the underwire should be rotated to a 2D plane with an external load to move the wire tips by 1cm to 2cm [23]. These flattened underwires and bands are purposely added to the bra sub-model. The process involves the following three steps (Fig. 9).

Step 1: Surface 1 is moved towards Surface 2 until the underwires are flattened.

Step 2: A face load is applied to the elements of the band until the surface is flattened.

Step 3: The underwires are relaxed to the initial relaxed condition by applying a point load at the end of the underwire to compensate for the tension that was originally found when the bra is donned. However, when simulating the wearing process of a wireless bra, these steps can be omitted.



a. 3D scanned model of a worn bra
b. Underwire is flattened
c. The band is flattened
d. Underwire and band are flattened
e. Point load applied to ends of underwire
f. Stress-free bra sub-model

Fig. 9. Making a stress-free bra sub-model from a 3D bra sub-model obtained from a body wearing a bra

2.4.2 Wearing underwired bra

As shown in Fig. 5, the simulation of the process of wearing a bra involves six steps.

Step 1: Apply gravity force to the breasts

The initial FE body sub-model was in a shape of supported breasts with an aim to identify the curves of breast roots. In order to simulate the natural shape of nude breast, it is necessary to apply a gravity load on the breasts (Fig. 10).

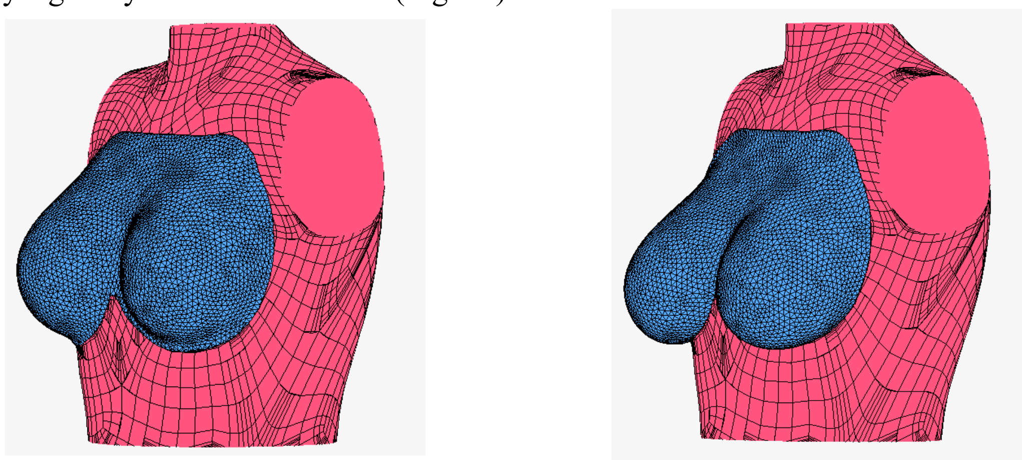


Fig.10. Applying gravity to breasts in body sub-model

Step 2: Push up the breasts

When a woman puts on a bra, she uses her hands to push her breasts superiorly and medially, so that the bra underwire sits correctly on the breast roots first, and then her breasts can be well contained in the bra cups. To simulate this process, a pair of cup-shape rigid surfaces like “virtual hands" were added to lift up the breasts until the breast roots were visible, and then the breasts were well housed in the “virtual hand" (Fig. 11). This novel method solved the challenging problems of penetration and local effects in modelling the contact of two deformable objects, and made the convergence in simulation achievable.

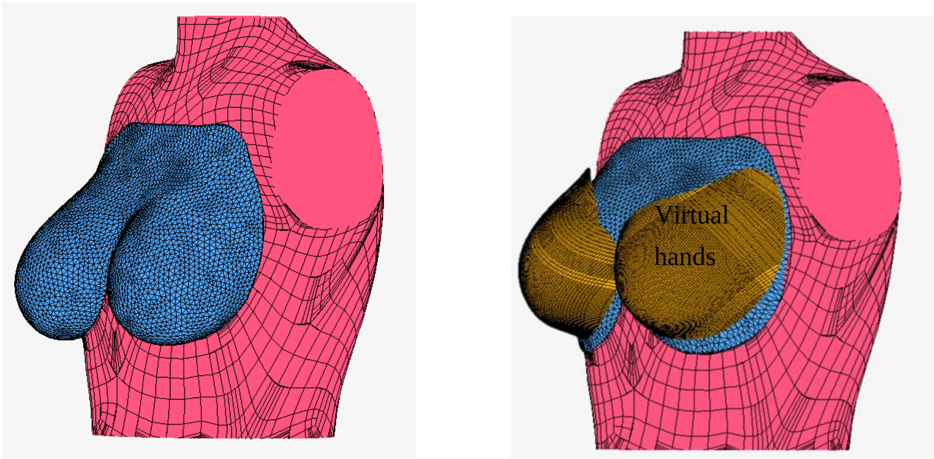
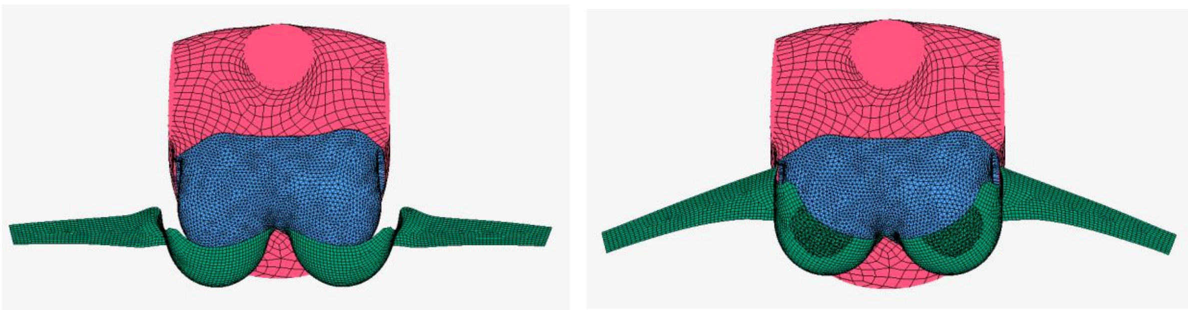


Fig. 11. Breasts being pushed by the virtual hands

Step 3: Align the underwire with breast roots

The most essential criterion of a good-fitting bra is that the underwire curves align with the breast roots. When the bra is being worn on the body, there is a tension to pull the lateral part of the two underwires towards the left and right underarm until the two underwires correctly match the lateral part of the breast root curve line. When moving the underwire to the body, the displacement boundary conditions were set properly at the outer most point of the underwire hence, the final position of the wire and the bottom curve of the cups could be aligned with the breast root (Fig.12). However when simulating the wearing process of a wireless bra, this step is not required.

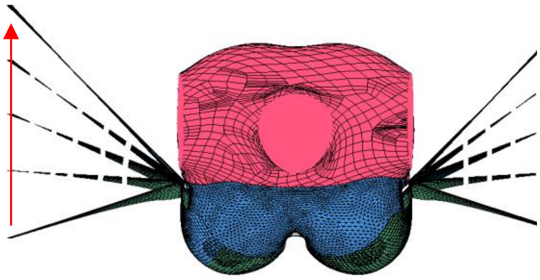


(a) Underwire prior to wearing (b) Underwire tip moved to the end of breast root

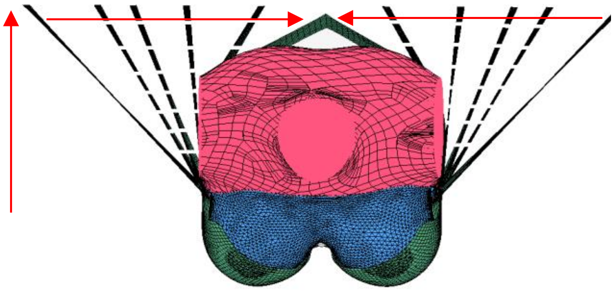
Fig. 12. Underwires moved to fit the breast roots

Step 4: Close the bands at the back of the body

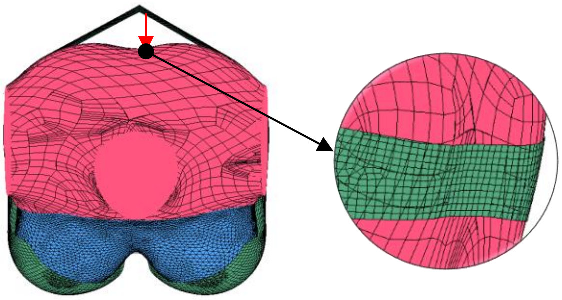
Another important criterion is appropriate tension of bra bands to secure the cups that support the breasts. The bands are stretched and fastened at the center back of the body, so that it wraps around the chest wall with comfortable tension. The friction in the tangent direction of the contact area between the band and the body prevents the breasts from sagging. The motion of closure was achieved by adding the proper nodal displacement at each node at the edge of band. Fig. 13 shows the process of closing the bra band. The arrow shows the band-closing direction. At this phase, the end of underwire was fixed.



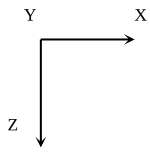
(a) Movement in the z-direction



(b) Movement in the x-direction



(c) Final movement in the z-direction



(d) XYZ axes in the coordinate system

Fig. 13. Means to close band at the back of the body

Step 5: Close the shoulder straps at the back of the body

The shoulder straps can provide the breasts mass a support together with the band. After enclosing the band at the back of the body, the next step is to make sure the shoulder straps stretch at the proper tension and close behind the body. Fig. 14 shows the process of closing the shoulder straps by adding the given nodal displacement at the end of straps in order to move them close to the band.

Fig. 14. Means to close shoulder straps at the back of the body

Step 6: Release the virtual hands

Once the underwire and band are placed correctly in position, the virtual hands were released. This is to let the bottom part of the breasts come into full contact with the cups due to gravity, and let the bands pull the springs of underwires for the necessary shaping of the breasts. The force that opens the underwire should be equal to the tension of the bra band which induces a reaction force to "push in" the breasts. Releasing the virtual hands allows the whole system to reach static equilibrium without external boundary conditions (Fig. 15).

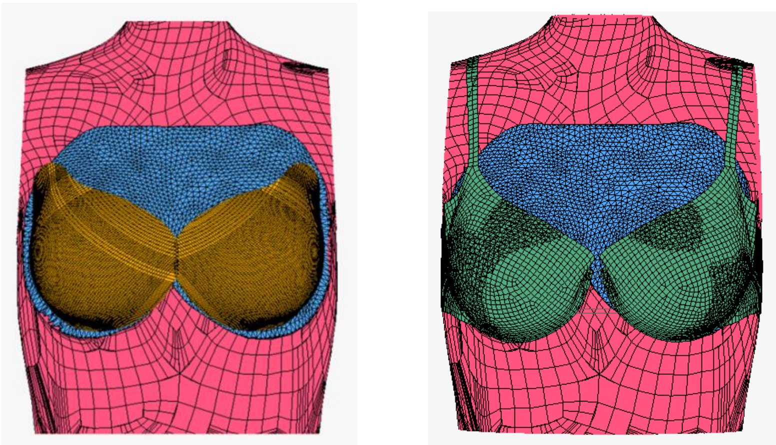


Fig. 15. Body sub-model before and after releasing the virtual hands

3. Results

3.1 Analysis of interaction between breasts and different bras in the contact model

The simulation results of an underwired bra and wireless bra being worn on the body were analyzed in terms of the displacement of breasts and the contact pressure.

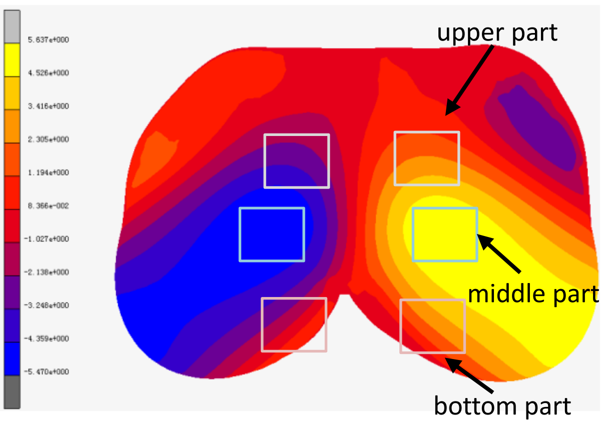
3.1.1 Displacement of breasts under gravity loading and wearing bras

Figs. 16a and 16b show the breast displacements after applying gravity. The gravity caused a maximum lateral displacement of -5.47 mm on the right and +4.53 mm on the left for the middle part of the breasts (-4.23 mm and +4.18 mm for the upper part, -3.99 mm and +4.32

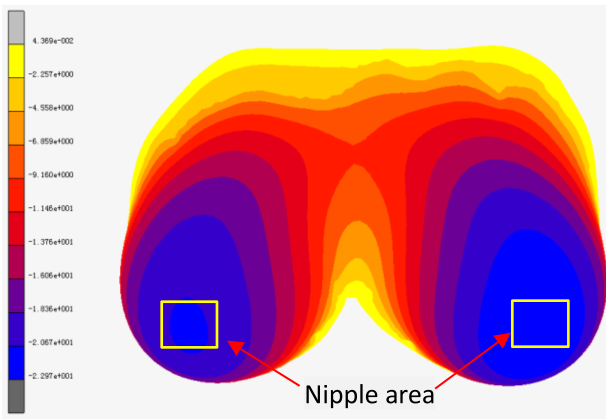
mm for the bottom part). A big inferior displacement of 22.9 mm was around the area of the nipples. This means that, due to the gravity load, the breasts were sagging more inferiorly than spreading laterally.

Regarding the breast displacements after wearing an underwired bra, Figs. 16c and 16d show that the upper part of the breast had +0.93 mm x-displacement on the right breast and -0.69 mm on the left. The middle part and the bottom part of the breast had a displacement of +2.17 mm and +4.68 mm respectively on the right; whilst -1.92 mm and -3.60 mm respectively on the left. It means that the function of bra caused more significant gathering effect at the bottom of the breast than other parts. The maximum superior displacement was only -6.20 mm in y direction, which reflected the lifting effect of wearing bra.

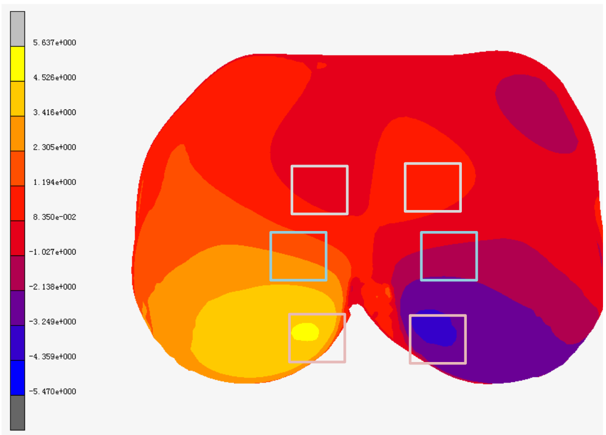
The wireless bra has smaller effect on breast gathering and lifting. Comparing Fig.16e&f with the braless condition in Figs. 16a and 16b, the wireless bra counteracted the gravity only slightly. It had an x-displacement of -3.98 mm on the right and +4.02 mm on the left in the middle part, y-displacement of -18.5 mm in the nipple area. Fig. 16e shows that the bottom part of the two breasts still had a trend to spread laterally ('-' on the right and '+' on the left). In the contrast, Fig. 16c shows that the underwired bra improved this situation by gathering the two breasts to the center ('+' on the right and '-' on the left).



(a) x-displacement after applying gravity

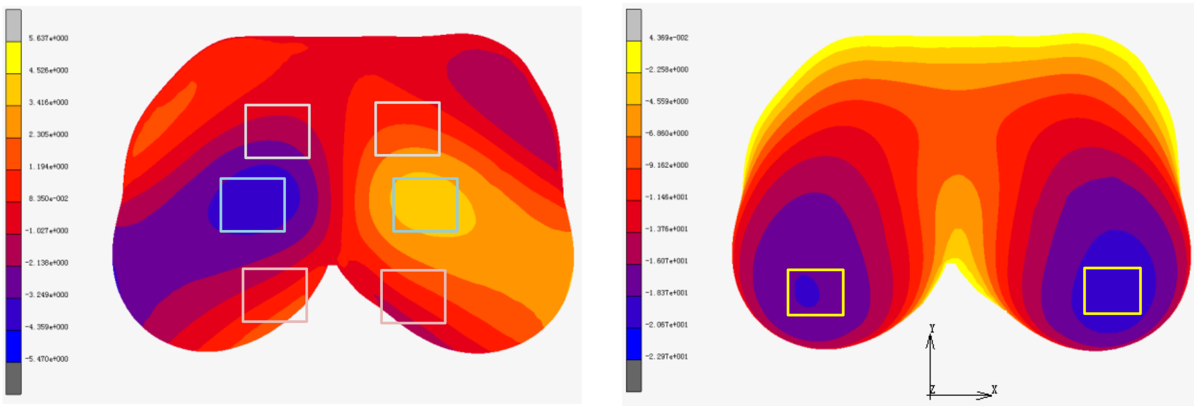


(b) y-displacement after applying gravity



(c) x-displacement after wearing an underwired bra

(d) y-displacement after wearing an underwired bra

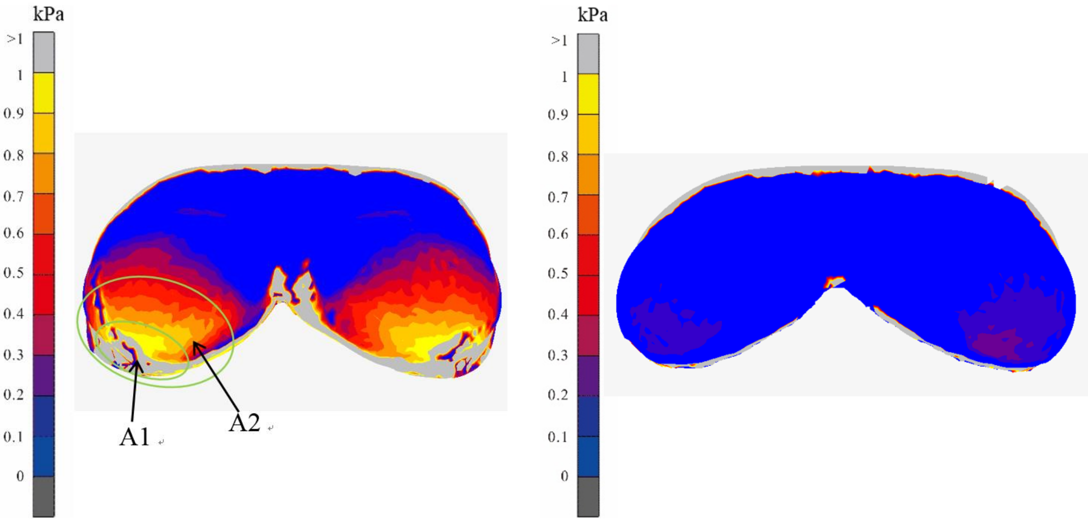


(e) x-displacement with a wireless bra (f) y-displacement with a wireless bra

Fig. 16. Simulated breast displacement after applying gravity and wearing a bras (underwired bra & wireless bra)

3.1.2 Contact pressure

As shown in Fig. 17a, the greatest pressure (0.8 kPa – 1.0 kPa) occurred at the bottom of the breasts (A1) followed by the lower breast area (A2) with 0.4 kPa - 0.7 kPa. Comparing with the simulation results of the underwired bra, the wireless bra (Fig. 17b) exerted a low pressure of 0.3kPa, which is only one-third of that in the underwire bra) onto the bottom of the breasts.



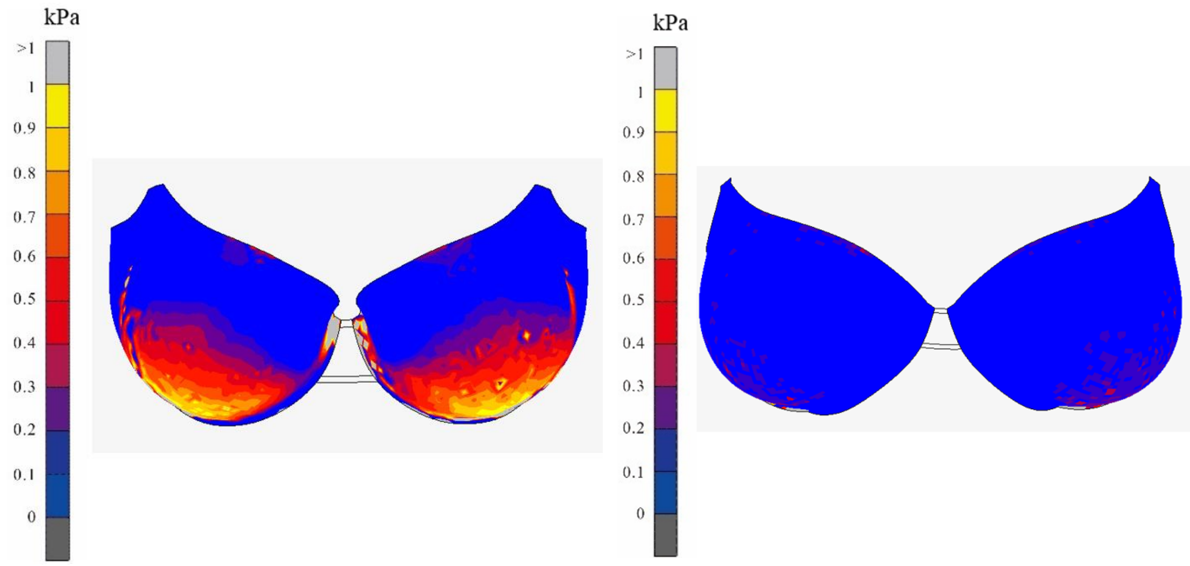
(a) Pressure distribution in underwired bra (b) Pressure distribution in wireless bra

Fig. 17. Simulated pressure distribution on the breasts exerted by an underwired bra and a wireless bra)

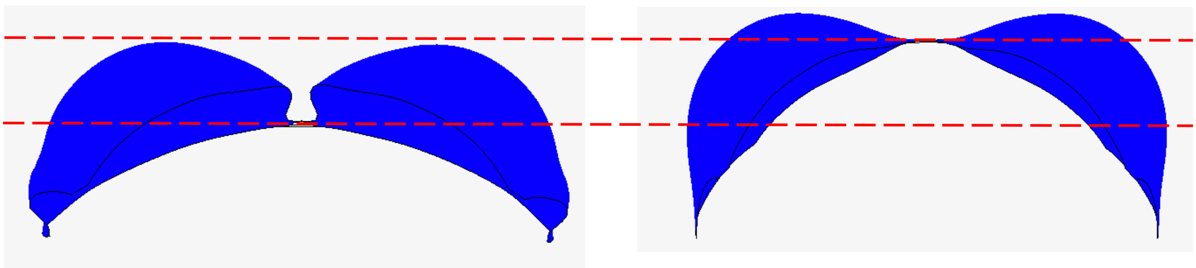
3.1.3 Pressure distribution, ultimate shape of bra and overall breast deformation

Pressure distribution

Fig. 18 presents the pressure distribution and ultimate shape of the underwired bra and wireless bras, when being fitted onto the body sub-model. Lower contact pressure occurred in the wireless bra than that in the underwired bra. In the absence of an underwire, the ultimate shape of the wireless bra was stretched laterally by the breast mass. This result is consistent with the real bra-wearing situation.



(a) pressure distribution of an underwired bra (b) pressure distribution of a wireless bra

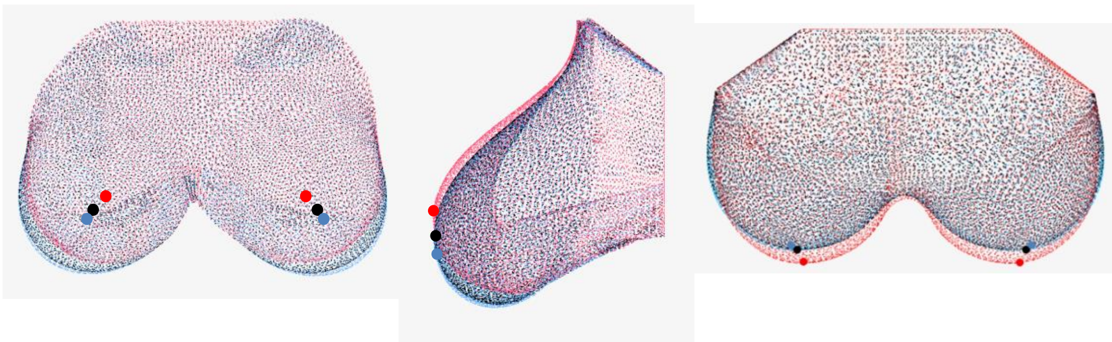


(c) ultimate shape of an underwired bra (d) ultimate shape of a wireless bra

Fig. 18. Pressure distribution and ultimate shape of an underwire bra and a wireless bra

Ultimate shape of bra

Fig.19(a) and (b) show the breast profiles in three bra-wearing conditions. The underwired bra obviously changes the breasts shape. However, the wireless bra can only change the breasts in a medium degree. The Fig.19(c) also shows that the underwired bra pushes the two breasts together from the side to the front center and makes the breasts look more rounded. This result of breast deformation matches with the real situation that bra-wearing can prevent the breasts from sagging down and spreading out.



(a) front view of breast (b) side view of breast profile profile (c) top view of breast profile

Fig. 19. Profiles of breasts in three conditions
(blue for braless, black for wireless bra and red for underwired bra)

Overall breast deformation

The measurements of simulated breast shape before and after wearing an underwired bra or wireless bra, is shown in Table 5, in terms of the percentage displacement of breast, ΔL_1, ΔL_2, ΔL_3, ΔL_4, ΔL_5 and ΔL_6

$$\Delta L_i = \frac{L_i - L_0}{L_0} \times 100\% \ (i=1,2,3 \text{ or } 4) \tag{3}$$

where L_0 is the original distance in the braless state, and L_i is the distance when the subject is wearing a bra. A negative change in L_1, L_2 and L_3, L_4 demonstrates that the bra has lifted up the breasts and pushes them towards the center-front of the body. A positive change in L_5, and L_6 means that the bra has made the breasts look fuller. Compared with the mean change of the underwired bra, the wireless bra shows smaller effects on the lifting and projection of breast shape. The actual body measurements after wearing underwired bra obtained from the fit experiment are also given in the form of bracket.

Table 4

Simulation results of breast deformation after wearing an underwired bra and a wireless bra

Measurement	Item		Braless	Underwired bra		Wireless bra	
			(mm)	L(mm)	Δ L(%)	L(mm)	Δ L(%)
Front neck point to right nipple	L_1		244.2	234.1 (233.2)	-4.1 (-4.5)	239.6	-1.9
Front neck point to left nipple	L_2		246.7	236.5 (235.7)	-4.1 (-4.4)	241.1	-2.3
Between 2 nipples	L_3		208.9	199.0 (199.9)	-4.7 (-4.3)	203.3	-2.7
Between 2 cleavage dots	L_4		105.1	96.3 (96.6)	-8.4 (-8.1)	102.1	-2.9
Breast projection	L_5	L	39.1	53.4 (54.1)	+36.6 (+38.4)	47.5	+21.5
		R	37.6	51.8 (52.3)	+37.8 (+39.1)	46.1	+22.6
Breast depth	L_6	L	82.4	89.1 (88.6)	+8.1 (+7.5)	83.8	+1.7
		R	79.1	82.6 (82.3)	+4.4 (+4.0)	80.6	+1.9

It is found in Fig. 20 that the effect of wireless bra on the breast deformation is almost three fifths the effect of underwired bra, in a significantly linear relationship (r^2 =0.983). It implies that they can be predictable from each other.

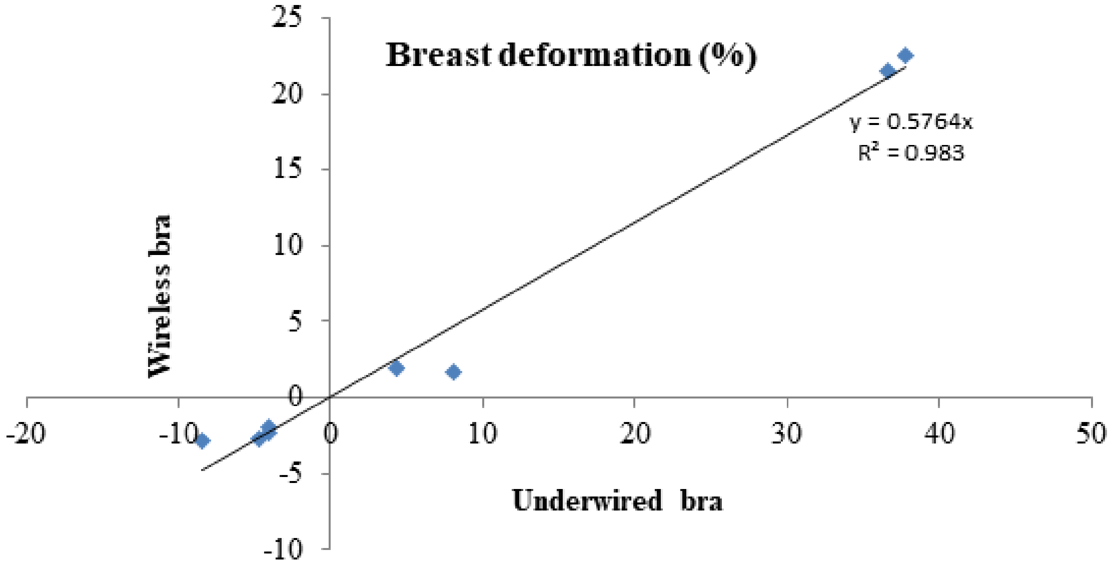


Fig. 20. Relationship between the underwired bra and wireless bra in their effects on breast deformation

3.2 Validation of simulation results with experimental data

3.2.1 Displacement of breasts

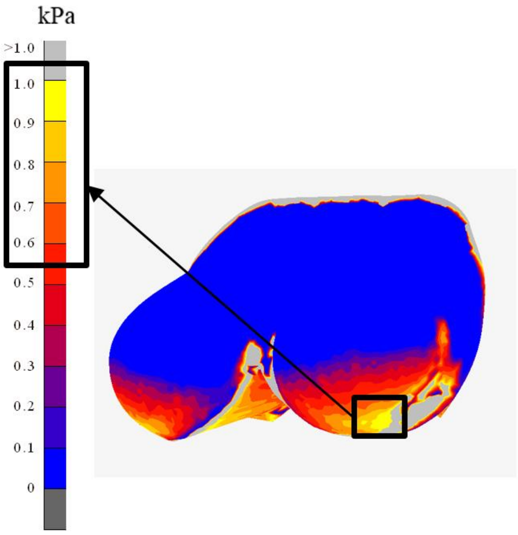
The simulation results of breast deformation in an underwired bra were validated based on the measurements (Fig.4) obtained from the in-vivio experiment of wearing an underwired bra. Table 5 shows that the differences between the predicted deformation of breasts via FE simulation and the experiment are within 10%. This indicates that the results of simulation with the FE method proposed in this study agree well with those of the experimental data.

Table 5
Simulation results of breast deformation caused by the underwired bra

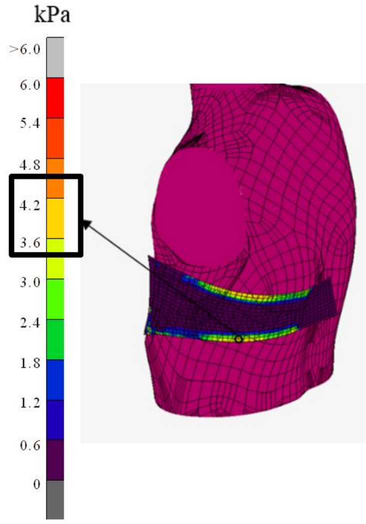
Measurement	Item		Experiment L(mm)	Experiment ΔL(%)	FE simulation L(mm)	FE simulation ΔL(%)	Error(%)
Front neck point to right nipple	L_1		233.2	-4.5	234.1	-4.1	8.9
Front neck point to left nipple	L_2		235.7	-4.4	236.5	-4.1	6.8
Between 2 nipples	L_3		199.9	-4.3	199.0	-4.7	9.3
Between 2 cleavage dots	L_4		96.6	-8.1	96.3	-8.4	3.7
Breast projection	L_5	L	54.1	+38.4	53.4	+36.6	4.7
		R	52.3	+39.1	51.8	+37.8	3.3
Breast depth	L_6	L	88.6	+7.5	89.1	+8.1	8.0
		R	82.3	+4.0	82.6	+4.4	10.0

3.2.2 Contact pressure

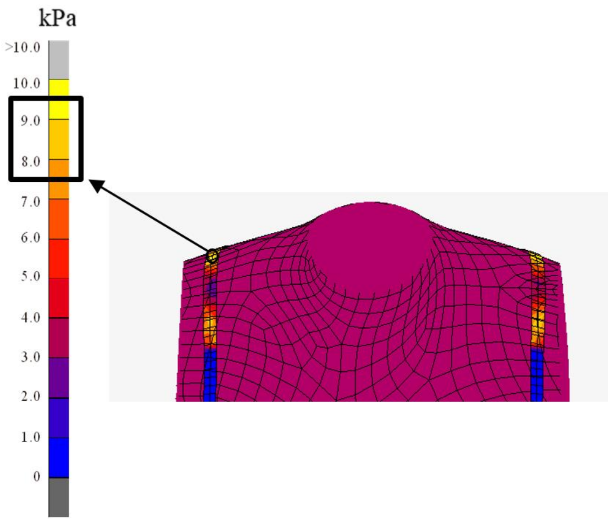
The cup pressure value ranged from 0.1 to 1.0 kPa in the pressure test. The simulation results of the pressure distribution (Fig. 21a) (0.6 kPa to 1.0 kPa) were in a good agreement with the measured range. For the pressure on the shoulder caused by the straps and side of the body under the bra band, the simulated pressure ranged from 7.5 kPa to 9.3 kPa and 3.6 to 4.2 kPa respectively, which was higher than the measured value (5.4 kPa for the shoulder strap and 2.2 kPa for the band) in the experiment.



(a) Pressure distribution (kPa) at the bottom of the breasts



(b) Pressure distribution (kPa) under the bra band



(c) Pressure distribution (kPa) under the shoulder strap

Fig. 21. Pressure distribution in FE analysis

4. **Discussion**

This research developed a customer-specific numerical model with a static analysis on the process of wearing an underwired bra and a wireless bra to observe the mechanical interaction between the bra components and body parts. In order to construct the bra try-on system, it is proposed to firstly release the tension of the bra, and then simulate the process of how a bra is stretched and fit with the body.

The breast FE sub-model was assumed to be uniform structure with the same material property. It is acknowledged that the simplifications may lead to some errors. For example, regarding the ultimate shape of breast (wearing an underwired bra) and the initial shape (free-gravity shape before wearing process), it is indicated that the maximum support of this simplified bra design cannot fully counteract the effect of gravity load. It is probably because of the over-simplified structure of breast without considering the ligaments, thus leading to the insufficient support for the breasts. This simplification also causes the errors in the validation with experiment. The displacement in the superior-inferior direction (L_1 or L_2) had an error of +8.9% and +6.8% respectively and the error in the medial-lateral direction (L_3) was 9.3%. This may have another reason explained for the errors which is the absence of the soft subcutaneous tissue and skin around the breasts. The neglection of these tissues will lead to over-constraint of the breast and the torso model during the wearing process.

In validating the pressure on the bottom breast exerted by the bra cup, the greatest pressure was 0.8 kPa to 1.0 kPa in the area contacting with the rigid underwire. This falls within the corresponding pressure range in the experiment. The pressure value under the shoulder straps (7.5 kPa to 9.3 kPa) and on the side of the body under the bra band (3.6 kPa to 4.2 kPa) was higher than the bottom breast due to the reason that the strap and band have less contact areas and harder contact bodies. The simulated pressure at these two parts was higher than the measured value (5.4 kPa and 2.2 kPa) in the experiment because the FE contact model let the fabric contact a rigid torso that has no subcutaneous tissue and skin. In the experiment, the pressure was lower because the soft tissues absorbed a part of the force exerted by the bra.

The simulated results are consistent with the real bra-wearing situation. When comparing the simulated results of wearing the wireless bra and the underwired bra, the wireless bra exerted lower pressure on the bottom of the breasts. When the underwired bra was worn, the shape of cup was stable and the breast mass inside the cup was evenly distributed. In contrast, in the wireless bra, the breast mass extended the cup fabric that made the gore tilted out ward and away from the sternum. For reshaping the nude breast, the underwired bra has a better performance in uplifting, gathering and protruding the breasts comparing with wireless bra. This indicates that the bra with no underwire cannot sufficiently support the breasts so that the breasts sagged and spread out. It is interesting to find that the effect of wireless bra on the breast deformation is three-fifth of the effect of underwired bra. Their linear relationship could be used to predict approximately the deformation of breasts with different materials of underwire. It confirms that the FEM is an useful tool to assist the bra designer to make predictions about breast deformation and pressure exerted by different bra designs, and thus reducing the time from designing to manufacturing.

The method proposed in this study provides a scientific way to investigate the interaction mechanism between a subject's breast and two different bras. The tension of underwired bra applied onto the human body can be readily and effectively released so as to mimic the realistic bra wearing process. This process of converting the bra from a 3D to a 2D configuration can help the bra designer to determine the 2D pattern of fabric of a given 3D surface. When the bra securely sits on the breasts, designer can also check the desired breast deformation and pressure distribution by altering the open gauge of underwire as well as the tension of band and shoulder straps in a 2D state. In addition, a more realistic wearing process of bra was completed from moving the underwire, shoulder straps and band to a proper position to adjusting the breast by "virtual hand", instead of sewing the 2D pattern to the body model [2,4,6]. The final static equilibrium condition of the complex function between the bra tension and breast with gravity loading was achieved through the wearing steps. It is believed that the wearing system based on biomechanical model predicts bra fitting on the real human body, outputting the ultimate shaping and pressure, which preparing the fundamentals of fit evaluation for bra designer. However, the limitations of this study are the single subject, simplified construct of the body model and homogeneous material of the breasts. The findings or relationships obtained from this study apply to this specific subject and bra style, but it requires further investigations about different breast sizes and bra types to confirm whether these findings can be used in a large population. Future studies are recommended to build a more realistic body sub-model with softer subcutaneous tissues and skin, an inhomogeneous material model of breast with adipose tissues, glandular tissues and ligaments to ensure a higher accuracy of simulation.

5. Conclusion

This study presents a novel bra try-on system based on numerical simulation to predict the effects of different bras on the breast shaping in terms of six pre-defined breast measurements, as well as the contact pressure. The simulation results of wearing an underwired bra are in a good agreement with the fitting experiment results. The success factor of this accurate prediction in the FEM is firstly the adoption of the hyper-elastic Mooney-Rivlin material for the breast sub-model. Secondly, two processes with the boundary conditions to release the tension of the bra before simulating the contact between the breasts and bra.

The simulation results of wearing an underwire bra and a wireless bra were also compared in terms of the pressure distribution and breast shaping. It was found that the wireless bra exerted less pressure on the breasts, and the shaping effect of wearing an underwire bra is superior to the wireless bra. This result is consistent with the actual bra-wearing.

This study has limitations, in that the geometric sub-model of the human body is overly simplified. Other than the uniform construction of breasts, the torso was considered as a rigid body part which increased the simulated pressure on the side of the body. Future work should therefore consider the adipose tissues, glandular tissues and ligaments. The body model can be modified by adding subcutaneous tissues with skin.

The validated FEM model discussed in this paper can be used to predict the deformation and contact pressure with reasonable accuracy and help to provide a better understanding of the complex interactions between the breasts and stretchable fabric. This method can show the visual changes of the 3D profile of the body after wearing a bra, as well as the contact pressure at each part of the bra. Bra designers and customers will therefore benefit from utilizing the model in designing bra patterns and choosing suitable bras. It is predicted that if this method is combined with a machine learning model to establish a database for customers, the method will predict the deformation and contact pressure for more design conditions in real time.

Acknowledgement

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Declarations of interest

None

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