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Numerical simulation of nonlinear material behaviour: Application to sports bra design

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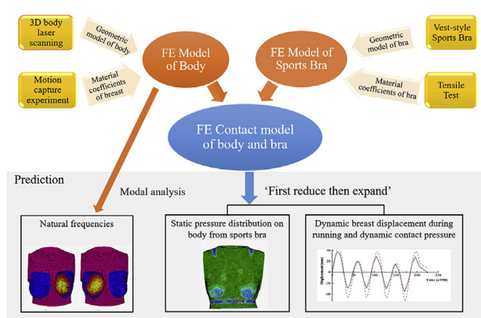
HIGHLIGHTS

- Material parameters and 'first reduced and then expanded' boundary conditions to solve penetration problems are introduced.
- Validated by experiments, the FE contact model can predict the contact conditions between the garment and human body.
- The highest amount of contact pressure between the bra and body was found on shoulders and increased during movement.
- The natural frequencies of the system of breasts and sports bra were significantly greater than those of bare breasts.

GRAPHICAL ABSTRACT



Numerical simulation of nonlinear material behaviour

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ABSTRACT

Compression sports bras are designed to protect the breasts by compressing them against the chest wall during physical activities. However, scientific analyses of the mechanical interactions between the body and sports bras have been largely absent. Therefore, the aim of this study is to simulate the static and dynamic contact conditions and dynamic displacements by using a finite element (FE) analysis. The FE model of the body is constructed with a rigid torso, hyperelastic breasts, and subcutaneous tissues. Scanning is carried out to obtain a geometric model of the body. The material coefficients of the breasts are determined by examining the differences between the FE-modelled results and experimental data. The FE contact model of a female body and sports bra is used to calculate the static and dynamic contact pressure, dynamic displacement of the breasts, and natural frequencies of the breasts with and without donning a sports bra. The calculated root mean square errors are less than 1%, which shows a good agreement between the FE results and experimental data. The FE contact model in this study provides a better understanding of the interaction between sports bras and the body and theoretical support for compression sports bra designs.

1. Introduction

The coupling of finite element (FE) modelling and practical experiments to find optimum design parameters has been widely used in the engineering disciplines to validate the behaviours,

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relationships and properties of both living and non-living entities, such as beams [1], engineering materials [2], manufactured biomaterials [3,4] human muscles [5] and protective gear [6]. Recently, advancements in computational modelling have extended FE modelling to the breasts, which is commonly done in clinical or industrial practices, such as detecting breast anomalies [7,8], predicting breast displacement [9,10], assisting with breast surgery [11] and determining the material parameters of breast tissues [12,13]. However, the mechanical behaviours of soft tissues, such as the breasts, are in fact more complex than most engineering materials and structures because breasts have viscoelastic and anisotropic properties [14].

Despite the complexities of the breasts, the apparel industry [15,16] still produces commercial sports bras that tend to compress the breasts against the chest wall to limit their movement during activities. Yet excessive pressure on the skin of the breasts can cause discomfort and is physiologically disturbing. While health and wellbeing are emerging research topics in the literature, scientific analyses of the mechanical interactions between sports bras and the human body have been largely absent. This poses as a challenge for the design of sports bras as it is difficult to model and optimise the nonlinear interactions between the viscoelastic breasts and elastic fabrics.

As for improving the perceived comfort of sports bras, the current practice is to reduce the contact pressure between the body and the sports bra under the premise of ensuring function. Previous studies have typically done so by carrying out experiments with subjects that focus on the interaction between a sports bra and their body [17]. However, the fabrication and fitting of prototypes on female subjects are time-consuming processes and prone to human errors. Instead, FE modelling is now being used to solve this problem, which has been an increasingly popular way to do so in the last few decades. For example, Li, Zhang and Yeung [18] presented a biomechanical model of the female body and a bra to determine the effects of the bra on the dynamic deformation of the breasts while the subject was walking at a constant speed. However, the FE model in their study was built by using the B-spline in the numerical analysis, not based on images of real human bodies. Additionally, the lack of authenticity in their study is attributed to parts of the breast being elastic and other parts being rigid. They did not consider gravity, which means that the initial pressure of the bra was not considered. Bel-Brunon et al. [19] developed an FE contact model and calculated normalized von Mises stresses for a bra worn without considering gravity. The results showed that the vertical displacement of the nipple with a donned bra is greater than that without a donned bra. The deficiencies of previous research works show the difficulty of applying FE analyses to solve the contact problems between women and bras. The major challenge is the penetration problem in modelling the contact mechanics. Furthermore, the complexities of the breasts make it difficult to numerically process them, and therefore, they need to be simplified [20].

To overcome these shortcomings, the static and dynamic contact conditions and dynamic displacement of the breasts are simulated in this study by using an FE analysis, the damping ratio is measured by using motion capture data and the natural frequencies of the bare breasts and breasts when a sports bra is donned as a support system are calculated. In doing so, a better understanding of the contact between a compression sports bra and the body is provided, which contributes to improving the process of developing new sports bras without the need to involve human subjects in wear trials. Moreover, the new method provides a more efficient, accurate and robust means of solving not only the complex problems of body-bra interactions but also other design applications in which the properties of the materials are highly nonlinear and viscoelastic in nature.

2. Methods

2.1. Experimental works

2.1.1. Surface topography

Women with large and hypertrophic breasts face more difficulties because their breasts jiggle and move, thus interfering with the ability to take part in daily and physical activities [21]. Hence, a 50-year-old healthy female subject with a cup size of 75D based on the metric sizing system was recruited to voluntarily take part in an experiment. The subject underwent scanning with a three-dimensional (3D) laser body scanner (Vitus, Human Solutions, Germany) which was set to scan at a high resolution of 300 pixels/cm^2 to construct geometric models of her body and breasts. The study was approved by the Human Ethics Committee of the Hong Kong Polytechnic University (HSEARS20151207004). The subject was informed about the purpose of the study, and then signed an informed consent form before taking part in the experiment.

2.1.2. Motion capturing experiment

The dynamic displacement of the breasts during running was captured by using 12 digital cameras (Eagle Motion Analysis Corporation, USA). Eleven spherical retro-reflective markers were attached to landmarks on the body of the subject (see Fig. 1). In this study, only two degrees of freedom were considered (y-direction and z- directions). Therefore, one marker was placed on her torso to record body movement. The other markers were placed on her breasts. Subsequently, the subject was asked to stand still, which served as the initial condition for each cycle of activity. Afterwards, the subject was instructed to run on a treadmill until she reached a steady speed. The coordinates of the eleven markers were subsequently recorded with time. The motion capturing experiments were conducted in two conditions: with and without a sports bra. The data collected in the latter condition were used to determine the material coefficients of the breasts, while those collected in the former condition were used to validate the FE model.

2.1.3. Pressure test

The actual contact pressure between the body and sports bra was tested by using a pressure sensor system (Novel Pliance-X). Two different types of sensors were used to measure 5 points: the left and right shoulders (Points 1 and 2), left and right underarms (Points 3 and 4), and bottom of the left bra cup (Point 5) (Fig. 2). Points 1 to 4 were tested by using a single sensor and Point 5 with a 2 * 2 matrix sensor because of the large area that needed to be measured. The contact pressure changed with each breath taken by the subject and each small movement that she made. In this study, the tested pressure is calculated by averaging over the stationary phase.

2.2. FE analysis

2.2.1. Material coefficients of breasts

The geometric model of the body was meshed with 6-mm 4-node tetrahedral elements. In order to examine the mesh sensitivity of the FE model, five FE models with different mesh sizes (2 mm, 4 mm, 6 mm, 8 mm and 10 mm) were built to determine the influence of the mesh density. It was observed that there is only a 0.26% variation in the dynamic breast displacement between the results with the use of 4 mm elements and 6 mm elements. However, the calculation time for the model with 4 mm elements is 3 times more than that with 6 mm elements. Therefore, 6 mm elements were used for both accuracy and efficiency of calculation time. The geometric model of the body contained a total of 119,510 elements, in which the model of the breasts had 22,931 elements.

Following previous studies [12,22], a Mooney-Rivlin material model with 5 coefficients (C_{10}, C_{01}, C_{11}, C_{20}, and C_{02}) was used to

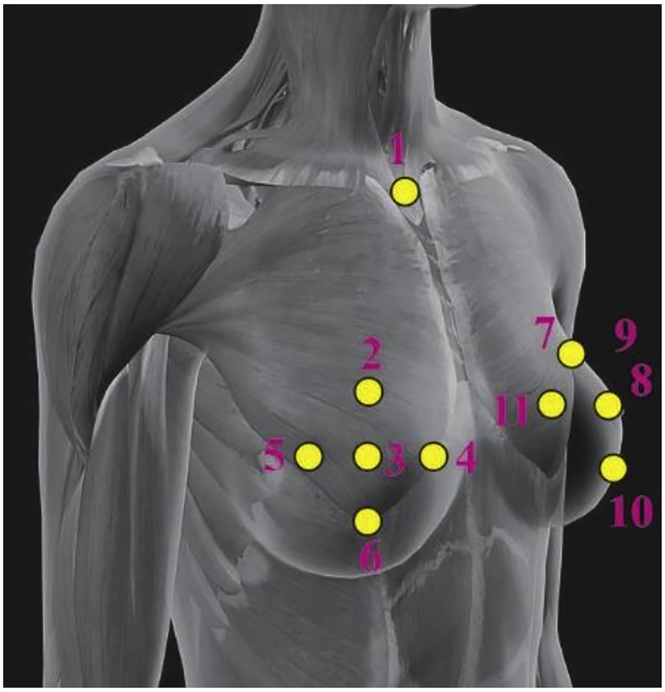

Fig. 1. Marker positions on breasts (Marker 1: sternum; Marker 3: right nipple; Marker 8: left nipple; and Markers 2, 4, 5, and 6 are 4 cm away from Markers 3 and 8).

construct the breasts with the FE software Marc (MSC Marc 2014.2.0, US). This material model has been proven to have the ability to simulate large deformations and nonlinear mechanical behaviours of soft tissues [13].

A series of computing analyses were carried out to determine the appropriate coefficients of the breasts. The boundary conditions of these analyses were gravity loaded to the breasts and the boundary displacement was extracted from the motion capture experiment on the torso part. The differences between the displacement of the bare breast condition in the experiment and that in the FE analysis results were compared and minimized. The initial sets of the coefficients of the Mooney-Rivlin material model for the breasts and layer of subcutaneous tissues were based on those in Samani et al. [22].

To obtain the coefficients, iterative changes were made to the inputted coefficients to simulate the breast displacement during running. In this study, there are smaller displacement in the x-and z-directions versus the predominant displacement in the y-direction during treadmill running. Moreover, displacements of the torso and breast in the x-direction very much relied on the arms, which moved back and forth during running. Thus, only the displacement in the y- and z-directions was considered. The criterion for the difference is the root mean square error (RMSE):

$$\mathrm{RMSE} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(\frac{\Delta Y_{exp,i}-\Delta Y_{FEM,i}}{\Delta Y_{exp,i}}\right)^2} \tag{1}$$

where ΔY_{exp} is the displacement of the nipple in the y-direction from the experiment, ΔY_{FEM} is the displacement of the nipple in the y-direction from the FE analysis results, and n is the number of sample data points.

Another critical material property is the damping ratio [23], which is important for simulating viscous materials in FE modelling [10]. To investigate the damping ratio of the breasts, the displacement of the breasts was analysed during a free vibration test [24]. During this test, the subject was asked to raise one of her breasts and hold it for a few seconds. Then, she was to remove her hand quickly to let the breast fall freely due to the breast mass and inertia.

The viscous damping ratio was calculated by using a logarithmic decrement, which is written as follows:

$$\delta = ln\left(\frac{y_n}{y_{n+1}}\right) \tag{2}$$

where δ is the logarithmic decrement, and y_n is the amplitude at the n_{th} peak of the damped waveform.

The damping ratio ζ can be calculated as follows:

$$\zeta = \frac{\delta}{\sqrt{(2\pi)^2+\delta^2}} \tag{3}$$

To ensure the reliability of the data, two curves were selected to calculate the damping ratio of the breasts, which yielded ζ_{mean}=0.273.

2.2.2. Compression sports bra model

The geometric model of the sports bra was extracted from the gravity-free model of the body. The entire model of the bra was meshed by using 6 mm quadrilateral elements. The mechanical properties of the bra fabrics were tested by using the constant-rate-of-extension tester Instron 4411. The sports bra was divided into 4 parts: shoulder straps, back panel, bra cup, and bra band. To describe the mechanical properties of the bra and reduce computing time, the sports bra was modelled as a two-coefficient Mooney-Rivlin material.

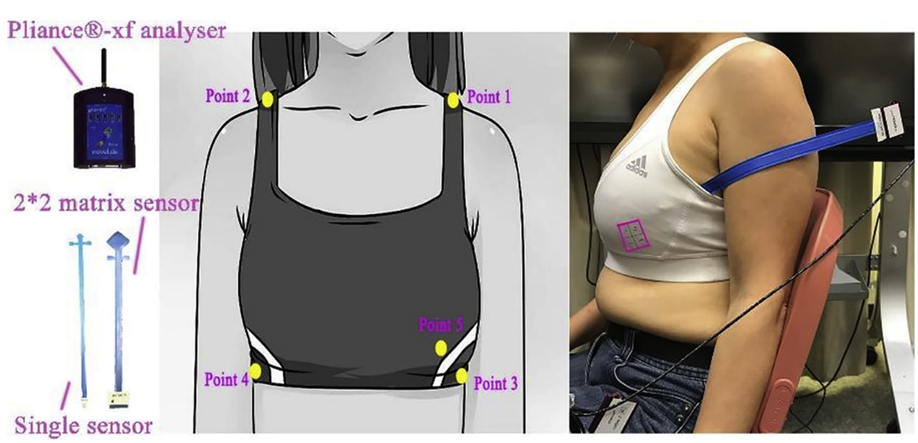

Fig. 2. Testing contact pressure.

Table 1
RMSEs of different material coefficients.

Compensation factor α	5	4.5	4	3.5	3	2.5	2
RMSE/%	3.34	1.68	1.39	0.32	0.21	2.86	6.77

2.2.3. Loading and boundary conditions

The FE model of the body was initially based on the subject in a standing position. A force with the same magnitude as gravity but in the opposite direction was added in order to construct a static equilibrium position of the breasts, which means that no external force was applied to the breasts.

The first problem was penetration in the contact model. To solve this problem, the model of the body was first reduced and then expanded [25], which involves the following steps:

1) the size of the original model of the body and bra was geometrically reduced. The scale factor for shrinking was 0.97 in each direction (x-, y- and z-directions). Sports bras expand during wear. Hence, the model of the bra in the initial state had to be smaller than the original model
2) the model of the body was shrunk, during which the gap between the models of the body and the sports bra was noted;
3) the model of the body was geometrically expanded. This expansion was done in Marc (MSC Marc 2014.2.0, US) by adding a thermal expansion property, which means that the volume increases with temperature. The end of the expansion was when the size of the model of the body reached the original size and calculated by using the Eqs. (4) to (7); and
4) gravity load was applied onto the breasts.

The static contact pressure between the sports bra and the body was analysed by using the steps described above.

Assuming that the initial temperature in the FE models is T_0, the initial volume of the model of the body is V_0, and the volumetric coefficient of the thermal expansion is $\alpha_{v,}$ which results in

$$\alpha_v = \frac{1}{V_0}\frac{\Delta V}{\Delta T} \tag{4}$$

where ΔV is the variation in the size of the model of the body and ΔT is the temperature variation.

$$T = k*t \tag{5}$$

where T is the temperature, k is a user-defined proportionality coefficient and t is time. Hence, Eq. (5) can be rewritten as follows:

$$\alpha_v = \frac{V_s - V_0}{V_0(T_s - T_0)} = \frac{V_s - V_0}{V_0(kt_s - T_0)} \tag{6}$$

$$t_1 = \frac{1}{k}\left(\frac{V_S - V_0}{\alpha_v V_0} + T_0\right) \tag{7}$$

where t_s is the end of the expansion of the model of the body, T_s is the temperature at time t_s and Vs is the size of the model of the body at time t_s.

The dynamic FE contact model was used to simulate the breast displacement and contact pressure during running. The friction coefficient used in this study is 0.4. As the breasts were attached to the torso part of the body with the glue contact option, the boundary displacement extracted from the motion capture experiment was applied to the torso part. The applied boundary displacements were simplified to two degrees of freedom (y- and z-directions).

3. Results and discussion

3.1. Material coefficients of breasts and sports bra

Three steps were carried out to obtain the optimal material coefficients of the breasts. The initial set of coefficients of the breasts was $C_{10} = 0.31$ kPa, $C_{01} = 0.3$ kPa, $C_{11} = 2.25$ kPa, $C_{20} = 3.8$ kPa, and $C_{02} = 4.72$ kPa. The first step was to determine the optimal range of material coefficients for the FE model of the body without a sports bra. The FE model using Mooney-Rivlin material with smaller coefficients should have smaller amplitude during vibrating. It was observed that the experimentally measured amplitude of the breast movement is 10 mm smaller than the simulated amplitude by using coefficients that are 5 times smaller than the initial set of coefficients (was $C_{10} = 0.062$ kPa, $C_{01} = 0.060$ kPa, $C_{11} = 0.450$ kPa, $C_{20} = 0.160$ kPa, and $C_{02} = 0.944$ kPa), and 4 mm larger than the simulated amplitude by using coefficients that are 2 times smaller (was $C_{10} = 0.155$ kPa, $C_{01} = 0.150$ kPa, $C_{11} = 1.125$ kPa, $C_{20} = 1.900$ kPa, and $C_{02} = 2.360$ kPa) than the initial set of coefficients. Therefore, the optimal material coefficients should be in this range. The second step was to input the coefficients of the breasts that were within this range into the FE model. A compensation factor α was defined to divide the initial set of material coefficients. The corresponding RMSEs are shown in Table 1. The third step was to find the minimized RMSE result for the different material coefficients. Table 1 shows that the optimal material coefficients are close to the

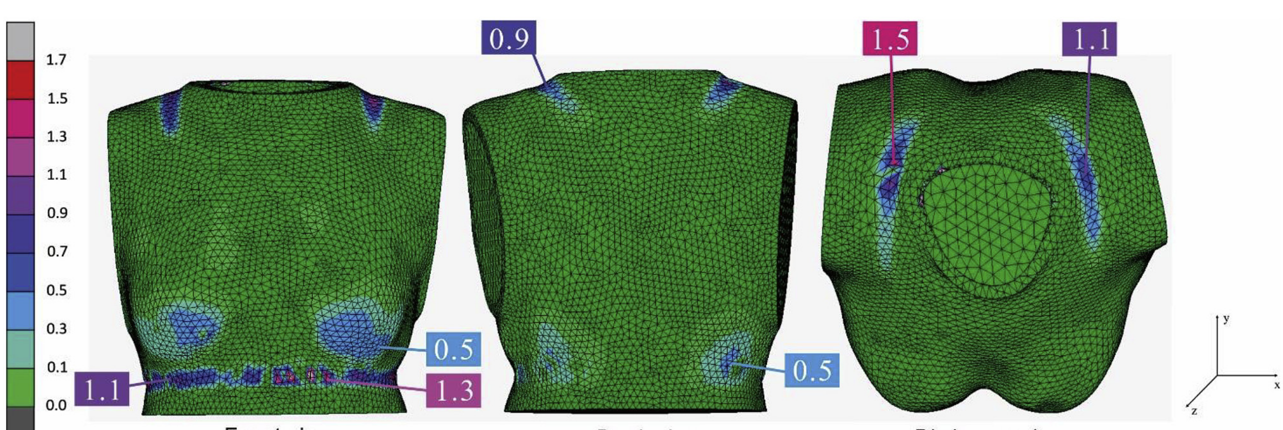

Fig. 3. Distribution of static contact pressure between sports bra and body.

Table 2
Comparison between simulated and tested results.

Position	Simulated contact stress/kPa	Tested contact pressure/kPa
Left shoulder	1.5	1.460 ± 0.016
Right shoulder	1.1	1.208 ± 0.012
Left underarm	1.3	1.125 ± 0.021
Right underarm	1.1	1.083 ± 0.018
Bottom of left cup	0.5	0.650 ± 0.043

coefficients when the compensation factor is 3. By adjusting the coefficients, the set with $C_{10} = 0.094$ kPa, $C_{01} = 0.108$ kPa, $C_{11} = 0.82$ kPa, $C_{02} = 1.18$ kPa and $C_{20} = 0.84$ kPa has the lowest RMSE, which is 0.0405%. Therefore, this set is selected as the optimal material coefficients of the breasts. Moreover, the calculated material coefficients of the sports bra fabric are $C_{10} = 200$ kPa and $C_{01} = -40$ kPa for the cup, $C_{10} = 197$ kPa for the back panel, $C_{10} = 200$ kPa and $C_{01} = -57$ kPa for the elastic bra band, $C_{10} = 300$ kPa and $C_{01} = -87.5$ kPa for the strap.

3.2. Static contact pressure

Fig. 3 shows the distribution of the contact pressure between the sports bra and the body in the static FE model. The highest contact pressure, 1.431 kPa, is found on the shoulders. The second-highest contact pressure is 1.272 kPa, which is caused by the elastic bra band. The highest contact pressure between the bra cup and the breasts can be observed at the bottom of the breasts, which is 0.477 kPa. These simulated contact stresses were validated through pressure testing experiments, and the comparisons are presented in Table 2. With accurate material coefficients, the FE model results agree with the experimental results. However, the simulated contact stress at the bottom of the cup is slightly lower than that in the experiments. This may be due to the simplified sports bra model. The bra cups of commercial sports bras have two layers, but the FE model simplified the bra to one layer.

3.3. Breast displacement and stress distribution in dynamic conditions

In this study, FE modelling is carried out to predict the dynamic displacement of the breasts during running at two constant speeds. To validate the contact model, the breast displacement obtained from the simulations was compared with that based on the motion capturing experiment with a sports bra. Fig. 4 and Table 3 show a

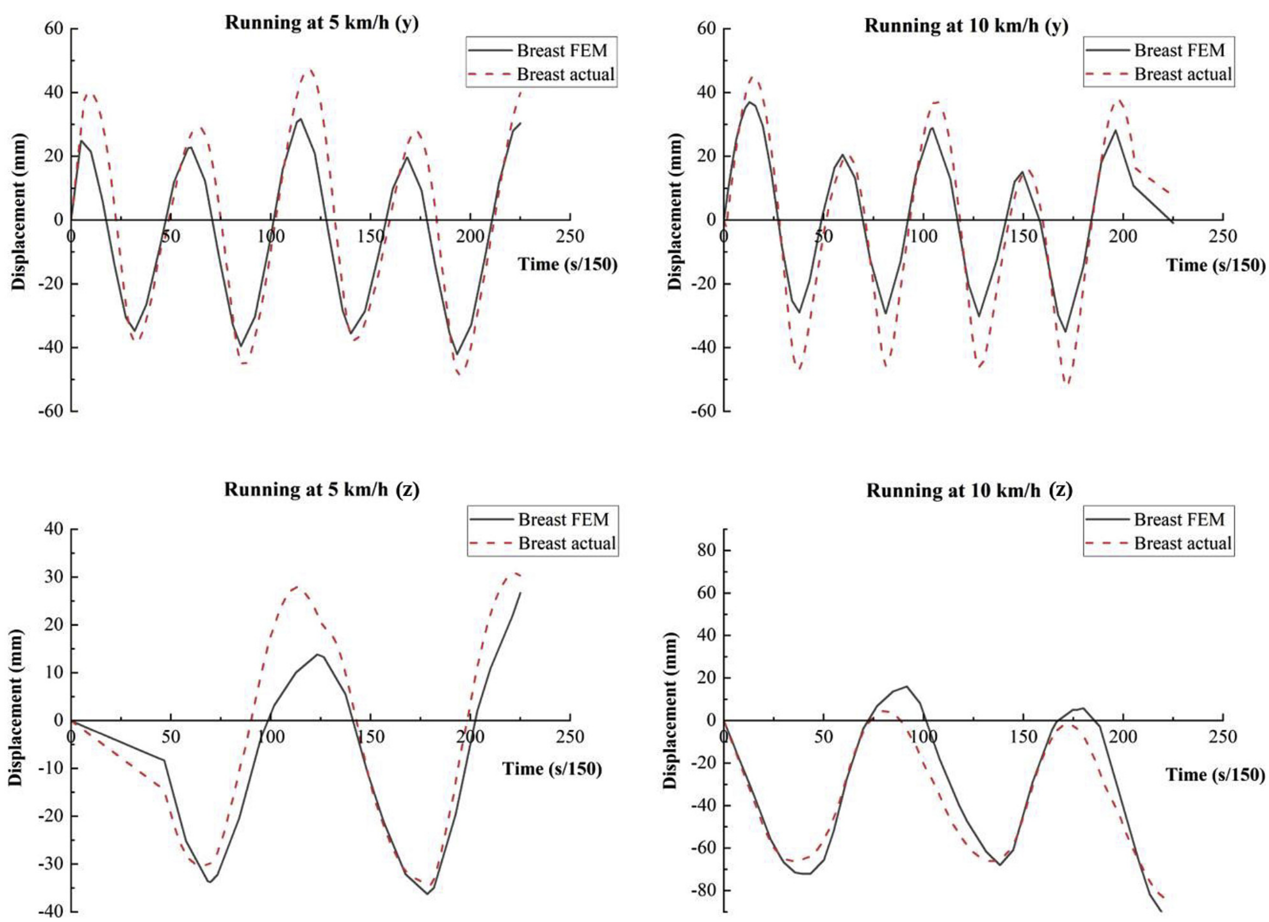

Fig. 4. Simulated and experimental breast displacement during running at two speeds with sports bra.

Table 3
The frequency and amplitude of breast movement during running.

Condition	Frequency (s^{-1})				Mean amplitude (mm)			
	5 km/h (y)	10 km/h (y)	5 km/h (z)	10 km/h (z)	5 km/h (y)	10 km/h (y)	5 km/h (z)	10 km/h (z)
Breast FEM	2.84	3.21	1.07	1.49	62.7	55.9	47.6	80.9
Breast actual	2.85	3.17	1.12	1.63	78.1	76.9	57.9	67.4

Table 4
RMSE percentage of simulated breast displacement.

Direction	Condition	RMSE%
y	Running at 10 km/h	0.7416
	Running at 5 km/h	0.5942
z	Running at 10 km/h	0.5064
	Running at 5 km/h	0.7941

comparison between the displacement in the simulation and experiment. The figure illustrates that the two methods show similar patterns of breast movement. The corresponding RMSEs are less than 1%, which is acceptable [10] (Table 4).

Not only can FE modelling accurately simulate the static contact pressure but can also be performed to determine the contact pressure during running. Since dynamic contact pressure is difficult to determine with the use of wired sensors, the FE method can be applied to solve this problem. The dynamic results showed that the amount of the contact pressure caused by the bra strap and the elastic bra band increases during movement. However, the contact pressure at the bottom of the bra cup is slightly reduced, probably because the compression sports bra used in this study is a simple vest-style bra. The breasts were mainly supported by the straps and elastic bra band during running. Additionally, the changes increased with a faster speed of running. The greatest change in the contact pressure caused by the strap and elastic bra band is 0.8259 and 0.3788 kPa, respectively. As the strap may cause the most discomfort, studying its dynamic contact pressure is important when designing a sports bra.

3.4. Modal analysis

To analyse the dynamic response of the breasts with and without a sports bra, a modal analysis was carried out and the natural frequencies were calculated. In reality, resonance occurs when the frequency of motion matches the natural frequencies of the human body. However, resonance is undesirable so if the natural frequencies of the breasts are known, this helps to prevent resonance [26].

In this study, the first 5 natural frequencies of the breasts with and without a sports bra are calculated by considering the viscous damping effect. The frequencies are reported in Table 5. The findings from the modal analysis demonstrate the importance of wearing a sports bra during physical activities. The step frequencies with different walking or running speeds were calculated by using $f = \frac{1}{T}$, which ranged between 1.5 and 5.0 Hz. In Table 5, the natural frequencies in the braless condition are all within this range. The natural frequencies of the breasts with the sports bra as a support system were found to be significantly higher than those in the braless condition. Since the step frequency during running easily reaches the natural frequency of the breasts, resonance can occur. Moreover, the breasts will oscillate with much greater amplitude, which can cause great discomfort. The human body and sportswear combined are supposed to have a higher natural frequency than the

Table 5
Natural frequencies with and without a sports bra.

Vibration	Condition		
	No bra		Sports bra worn
	Left breast	Right breast	
Frequency order	Magnitude of frequency (Hz)		
1st	2.074	2.075	5.585
2nd	2.198	2.203	7.242
3rd	2.533	2.569	7.575
4th	3.205	3.205	8.071
5th	3.298	3.307	8.801

step frequency during exercise. A modal analysis can improve the understanding of breast movement and provide the basis for predicting breast displacement in dynamic conditions. Therefore, a modal analysis can be used to validate the function of a sports bra or any other sportswear. This analysis proves that the FE model is an important and necessary tool for future studies that seek to address problems that involve soft tissues and garments.

4. Conclusion

A reliable FE contact model to simulate the distribution of contact pressure between the female body and a sports bra and breast movement due to dynamic conditions with a sports bra worn has been established in this study. For the static analysis, the highest contact pressure is found at the shoulders, and the least amount of contact pressure is at the bottom of the bra cup, which is in agreement with the results from the contact pressure testing. As for the dynamic analysis, breast movement is investigated and analysed when a sports bra is donned with contact pressure. Based on the calculated errors between the results of the FEM and experiments, the model is found to predict the contact conditions with good accuracy.

This study provides a robust method to simulate the contact problem between relatively rigid garments and soft tissues that have hyperelastic properties. This method can potentially provide the basis for future research work on apparel comfort, elastic materials, intimate apparel and sports activities. Improved sports bra designs will also contribute to the wellbeing of the female population globally.

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