Transaction

A 3D Biomechanical Model for Numerical Simulation of Dynamic Mechanical Interactions of Bra and Breast during Wear

Y. Li, X. Zhang, K.W. Yeung

Institute of Textile and Clothing, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

Abstract: This paper presents a 3D biomechanical model of a female body, which consists of elastic breast and rigid body on the basis of analyzing the biomechanical characteristics of human body. Bra is regarded as material linearity and geometric non-linearity. The contact between human body and bra is modeled as dynamic sliding interface based on the theory of contact mechanics. Finite element method is used in the time domain for deriving numerical solution of the dynamic contact problem. An example is presented to illustrate the simulation results of the computational model: a female human model is walking at a constant speed when wearing a bra. The computational model can simulate and characterize the dynamical mechanical behavior of the breast and bra during the body movement with the breast falling and bouncing in terms of bra deformation, pressure and stress distributions and breast stress distributions. Comparing with the quantity of measured garment pressure reported in the literature, the predicted pressure is close to the magnitude of experimental measurements, indicating that the model is able to simulate bra pressure during wear with reasonable accuracy.

(Received 3 December, 2001; Accepted 24 July, 2002)

1. Introduction

Bra is the most feminine of foundation garments that are required to satisfy the aesthetic needs and physiological health and comfort of the wearer. Generally, sports activity puts tremendous stress on breasts and the tissue surrounding them. A good bra offers the best supporting and protection against tissue damage in breasts. Most women are in their bra between 10 and 12 hours every day for a lifetime. Therefore, it is important to select and wear a bra that is good fit with support and pressure comfort.

To optimize the design of a bra with good support and pressure comfort, we need to study the mechanical mechanisms involved in the dynamic contact between breast and bra experimentally and theoretically. There are very limited publications in the literature in this area, particularly in theoretical investigation. A number papers have been published in Japan on the measurement of garment pressure and relevant subjective sensations in wear trials [5-7] [8]. Makabe et al studied the pressure of brassiere by letting subjects to wear brassiere samples that were designed in different shape, material and pattern [5]. Pressures were measured at 6 points under the bra. The pressure of the most comfortable brassiere sample was 24 mm Hg (32.40 g/cm²) at the point where the strap and the shoulder line cross, and 11~16 mm Hg (14.85~21.60 g/cm²) at the points under bust line and lateral top areas of the cup.

To achieve design optimization, we need thorough theoretical understanding of the mechanisms and processes about the physiology, psychology and physics of the breast and bra as the foundation of engineering design, which involves a number of aspects of research. Firstly, human body needs to be scanned and digitized as the actual shape and dimension of the body and breast have critical influence on the garment-skin contact process. Secondly, bio-mechanical models of the body and breast need to be developed as different parts of the body have different structural and material features. Thirdly, mechanical models need to be developed to describe the dynamic mechanical interaction between the body (breast) and garment with satisfactory accuracy. Finally, computational methodology to solve the models and computing technology needs to be developed to visualize the dynamic interactions.
In a previous paper [11], we reported the development of a biomechanical model to study the dynamic pressure distributions on knees during bagging process by using finite element method. The knee was modeled as a two-layer structure: a rigid ball (as the bone) covered by elastic shell (as the skin) because there is little soft tissue in this body part. The results of the numerical simulation show that pressure distribution between the skin and fabric is affected by the fabric extensibility in multi-directions. The pressure on human body is from two causes: the external pressure from garment deformation and the inner pressure due to the skin deformation.

To simulate the dynamic garment pressure distribution on a 3-dimensional human body during wear, we developed a 3D rigid human model based on the theory of contact mechanics by using finite element method [12]. The model is able to predict the dynamic mechanical behavior when the female body worn a set of perfect fitting garments is walking. Using the model, we can simulate the mechanical behaviors of garment deformation, garment pressure, internal stresses in the garment, and effects of garment’s weight and inertia force on the dynamic wearing process. Further, we developed a 3D bio-mechanical human model that consists of three layers of materials with different mechanical properties, i.e. the skin, soft tissue and bone [10]. This biomechanical human model is able to generate quantitative description of the mechanical behaviors of the garment: deformation and pressure distributions, as well as those of human body deformation and the inner stress in the skin. The predicted pressure is close to the magnitude of the measurements from subjective evaluation experiments of garment pressure.

In this paper, we report the development of a bio-mechanical model for numerical simulation of dynamic mechanical interactions of bra and breast during wear. Based on analyzing the mechanical characteristics of breast and bra, a mechanical model is developed based on the theory of contact mechanics. Finite element method is used in the time domain for deriving numerical solution of the dynamic contact model. A series of examples are presented to illustrate the simulation results of the computational model: a female human model worn a bra and is walking at a constant speed. The bras have the same style but are made from different material: a cotton denim fabric and a knitted nylon fabric.

2. Model development

2.1 Bio-mechanical and physical background

2.1.1 Bio-mechanical characteristic of breast

Breast is comprised of different structures, each with its own specific function. One-third of the breast is comprised of fatty tissue. The other two-thirds is made up of structural components called ducts and lobules. Fat fills the spaces between lobules and ducts. There are no muscles in the breast, but muscles lie under each breast and cover the ribs. Each breast also contains blood vessels and vessels that carry lymph. The breast increases in volume during pregnancy and generally weighs between 400-600 grams, increasing up to 800 grams during lactation [3]. Very weak ligaments that stretch easily support the breasts. The overlying skin of the breast offers only secondary support.

During wearing, breasts bounce with each foot-strike, and this repeated action accelerates permanent stretching of the skin and sagging. Easy stretched ligaments cause breast sag. Excessive breast motion is the most common cause of the movement discomfort during a physical activity. Therefore, the breast structures of lacking internal anatomical support requires some type of external support, including weight support, movement restriction, compression by flattening breast against the body, depending on individual wish and shape.

2.1.2 Mechanical characteristics of bra

A good design of 3D structural bra is probable the most important factor influencing bra’s functional performance and dynamic comfort during wear. It needs to construct bra in appropriate structure that induces basically load distribution in a bra. The front straps should be positioned so that they lie in a direct line of pull over the nipples, allowing for optimal vertical breast support. The strap fabric should also be wide to allow for greater force distribution to avoid straps digging into the shoulders. Fasteners, hooks and underwires should be covered to avoid irritations. A good bra doesn’t chafe around the armholes or ribcage. All of the factors should be considered in 3D-structure design of a bra. The contact interface between breast and bra can be regarded as dynamic coordinated contact, which represents the contact feature that the magnitude of the contact interface is comparable to the effective surfaces of woman body and bra.

Fabric stretch is another important factor influencing the effectiveness of the support. Bra should have enough elasticity to accommodate upper torso movement but prevent breast movement. It should be sufficiently elastic.
in the horizontal plane to allow for chest expansion while breathing. On the other hand, elasticity in the vertical plane should be limited to minimize vertical breast movement. Straps should have limited elasticity as well for the same reason. Fabric-stretch at multi-directions and frictional slippage generate the pressure from a bra over the skin surface. Generally, the mechanical properties of fabric are both lower tensile modules in large deformation and effective elastic recovery, which can be regarded as the mechanical properties of material linearity but geometric non-linearity.

2.1.3 Mechanical interactions between breast and bra

Figure 1 shows a woman wears a sport bra and walking in a constant speed \( V_w \). During walking, breast may bounce with each foot-strike, causing mechanical deformation in breast. Meanwhile, mechanical interaction occurs at the contact surface between the breast and bra that supports berates and compresses the breasts. The external forces on an element of the breast involve the gravity \( q_x \) on the breast, the interactive contact force \( q_y \) at the normal direction of the contact surface, the friction \( q_f \) as the bra slipping on the breast surface. Where, contact force \( q_x \) and friction \( q_f \) are interaction forces between breast and bra. The mechanical forces will cause the internal strain-stress and the inertia force \( q_i \) within the breast and the bra respectively.

Based on the analyzing the characteristics of breast and bra, we developed a mechanical model to simulate the mechanical interaction as a female body wears a sport bra and walks at constant speed \( V_w \), which results in up-down cycling motion of the body with speed \( V_y \), as shown in Figure 1, according to the analysis of the sports bio-mechanics during human walking [13].

![Fig. 1 Contact between breast and bra](image)

2.2 Model assumptions

On the basis of the analysis, we make the following assumptions:

1. The female body is assumed as bi-material body that consists in two material components within an object: elastic material for the breast part and rigid material for the other part.

2. The bra is considered as thin elastic shell with material linearity and geometric non-linearity; the stress in the fabric thickness is assumed to be zero.

3. The body always keeps in contact with the highest point of bra’s shoulder strap.

4. The contact between breast and bra is dynamic coordinated contact, due to the contact feature that the magnitude of the contact interface is comparable to the effective surfaces of breast and bra [4].

5. The friction between human body and the garment is neglected.

2.3 Model descriptions

![Fig. 2 The global coordinate system of the contact system](image)

Figure 2 shows the time dependent contact system between the female human and bra in a fixed global coordinate system \( x (x_1, x_2, x_3) \), corresponding to \( z, x, y \) coordinate as shown in Figure 1. In the system, bra is regarded in a domain \( \Omega^2 \), and human body in a domain \( \Omega^1 \) that consists in two connecting sub-domains of elastic breast \( \Omega^e_2 \) and rigid body \( \Omega^r_2 \) as shown in Figure 2. At time \( t=0 \), the bra and the human occupy domains \( \Omega^1 \) and \( \Omega^2 \) in their unrefracted configuration respectively. The human body and the bra are all simply connected so that there is no interior boundary in any of them, satisfying physical constraint:

\[
\Omega^1 \cap \Omega^2 = \emptyset \quad (t=0)
\]  

(1)

where \( \emptyset \) denotes a null space, indicating that \( \Omega^1 \) and \( \Omega^2 \) do not penetrate with each other.

From time \( t = 0 \), the human body moves to occupy new domain \( \Omega^1 \), contacting to the domain \( \Omega^1 \) of the bra at any time \( t > 0 \). The boundaries of \( \Omega^1 \) and \( \Omega^2 \) are denoted by \( \Gamma^1 \) and \( \Gamma^2 \), respectively, which consists of three components:

\[
\Gamma^n = \Gamma^n_e \cup \Gamma^n_f \cup \Gamma^n_c \\
^{n=1,2}
\]  

(2)
where, $\Gamma_\delta$ denotes prescribed displacements boundary, $\Gamma_l$ denotes prescribed load boundary, and $\Gamma_c$ denotes the contact boundary where contact may occur, and $\cup_\theta$ denotes the union operator.

### 2.4 The governing equations

#### 2.4.1 Motion equations

The motion equation of the bra at time t is

$$\sigma_{ij}(x) + 4\epsilon_{ij}(x) = \rho\ddot{a}_i(x)$$

\[ x \in \Omega^1; j=1 \text{ to } 3 \text{ and } i=1 \text{ to } 3 \]  \hspace{1cm} (3)

For the female body of bimaterial, the motion equation is written in the two sub-domains of elastic breast $\Omega^2$ and rigid body $\Omega^3$, respectively:

$$\sigma_{ij}(x) + 4\epsilon_{ij}(x) = \rho\ddot{a}_i(x)$$

\[ x \in \Omega^2; j=1 \text{ to } 3 \text{ and } i=1 \text{ to } 3 \]  \hspace{1cm} (4)

$$\epsilon_{ij}(x) = \rho\ddot{a}_i(x)$$

\[ x \in \Omega^3; j=1 \text{ to } 3 \text{ and } i=1 \text{ to } 3 \]  \hspace{1cm} (5)

where $t$ denotes time; $x$ a position vector; $u(x)$ the displacement field; $a(x)$ the acceleration field; $\sigma_{ij}(x)$ is the Cauchy stress components that give the actual traction on an imaginary plane at a point within an object; $\epsilon_{ij}(x)$ is the ith component of the strain $\epsilon_{ij}(x)$ on an object, $\rho$ is the mass density of an object which is assumed constant, and $a(x)$ is the ith component of the acceleration vector of a material particle within an object.

#### 2.4.2 Constitutive equations

For the bra and the breast of linear elasticity, the stress-strain relation is given by the generalized Hooke's law [9], i.e

$$\epsilon_{ij} = C_{ijkl} \sigma_{kl}$$

On $\Omega^1$ and $\Omega^2$, \hspace{1cm} \hspace{1cm} (6)

where $C_{ijkl}$ are material constants; $s_k$ is a component of second Piola-Kirchhoff stress tensor that is related to the Cauchy stress component $\sigma_{ij}(x)$; $\epsilon_{ij}$ is a component of Green-Lagrange strain tensor to describe the deformation of geometric non-linearity, which consists in linear and non-linear components $\epsilon_{ij}$ and $\eta_{ij}$:

$$\epsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i})$$

$$\eta_{ij} = \frac{1}{2}(u_{k,i} + u_{k,j})$$

\[ \text{where, } \epsilon_{ij} = \frac{\partial u_i}{\partial x_j}, \eta_{ij} = \frac{\partial u_i}{\partial x_j} \]

On $\Omega^1$ and $\Omega^2$, \hspace{1cm} k=1 to 3 and i=1 to 3.

#### 2.4.3 Initial speed

Initial speed is exerted on the rigid body part, which consists in two components: horizontal motion with speed $V_x$ at $x_3$-direction and up-down motion in speed $V_y$ at $x_3$-direction, which are presented as:

$$V(x) = V_x$$

$$V(x) = V_y$$

On $T^2$, \hspace{1cm} \hspace{1cm} (7)

#### 2.4.4 Displacement boundary condition

According to assumption 3, the shoulder strap of the bra has the same movement with the body. The displacement boundary conditions on these contact points are represented as follows:

$$u_i(x) = u_i(x) \quad \text{and} \quad u_i(x) = u_i(x)$$

On $T^2$, \hspace{1cm} \hspace{1cm} (8)

#### 2.4.5 External force

Gravity exerted on the bra, the breast and the rigid body part is expressed as:

$$q^e = \rho g$$

On $\Omega^1, \Omega^2, \Omega^3$ \hspace{1cm} \hspace{1cm} (9)

where, $g$ is gravity acceleration.

#### 2.4.6 Contact conditions

For the frictionless contact interfaces, denoting the contact force $q^n$, then by Newton's third law, we have

$$q^n = q^n + q^n$$

On $\Gamma_c$, \hspace{1cm} \hspace{1cm} (10)

where, $q^n$ is the component of contact force $q^n$ in the normal direction of contact points. The mechanical contact condition as a constraint on the normal contact
force \( t_{q_1}^n \) is:

\[ t_{q_1}^n \leq 0 \quad \text{on} \quad \Gamma_c^1 \cup \Gamma_c^2 \quad n=1,2 \]

It means the interactive pressure is exerted on the object against its normal direction of the contact boundary points. The model is solved numerically with the finite element method in space domain and the finite difference method in time domain by using an explicit, nonlinear finite element analysis program [1].

3. Application of the model

3.1 Generation of 3D finite element models

We develop finite element models based on 3D surfaces by B-spline approach. Belytschko-Lin-Tsay shell element [1] is used in the discretization of the 3D surfaces of the female body and the garment. The bi-material model of the female body is constructed by tied the nodes of the elastic breast to the rigid chest, as shown in Figure 3. The finite element model of the bra is shown in Figure 4. The total element number of the female body is 24790 (5770 elements for the breast, 19120 for the rigid part), and 2386 for the bra.

![Fig. 3 Finite element model of the body](image1)

![Fig. 4 Finite element model of the bra](image2)

3.2 Material properties

Table 1 Mechanical parameters of the materials used in the computing

<table>
<thead>
<tr>
<th>Components</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Bone</td>
<td>Density (kg/m³)</td>
<td>*1579</td>
</tr>
<tr>
<td></td>
<td>Compress Modulus (kg/m²)</td>
<td>*489000</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>The breast</td>
<td>Density (kg/m³)</td>
<td>2250</td>
</tr>
<tr>
<td></td>
<td>Tensile Modulus (kg/m²)</td>
<td>2500</td>
</tr>
<tr>
<td>Bra</td>
<td>Density (kg/m³)</td>
<td>455</td>
</tr>
<tr>
<td></td>
<td>Tensile Modulus (kg/m²)</td>
<td>3500</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio</td>
<td>0.32</td>
</tr>
</tbody>
</table>

*\([13] \wedge [2]\)

We estimate the mechanical properties of the human body from the published data in the literature [2][13]. The breast density is estimated from its weight and volume. The tensile modulus of the fabrics are tested in Instron tensile machine and the Poison’s ratio is estimated from the measurements of Kawabata bi-tensile test. Table 1 shows the mechanical parameters of the materials used in the computing.

3.3 Simulation conditions

In the simulation, we assume that the female model is walking at initial speed \( V_o \), which results in a cycling motion of the body at the y direction with speed \( V_y \). \( V_y \) is specified as 10 cm/s and \( V_y \) as 30 cm/s, and the time period of motion is 0.05 second. Thus, the movement amplitude of the human body at y-direction is about 1.5 cm in the motion period. The time step size is 1.08E-4 second, which can be adjusted according to need to the computing stability. The numerical computation is implemented by using commercial finite element software [1].

4. Computational results

4.1 Breast bounce process

Figure 5 shows the breast bounce process with the body movement with three views. Figure 5(a) shows the fitness of the bra with the breast as the body rests; 5(b) as the falling position of the breast in the initial stage of the body movement; and 5(c) as the bounce-up position of the breast in the later stage of the body movement. Figure
5(b) shows that the bra as a slave object can fit the breast by stretch, while Figure 5(c) illustrates that it cannot fit the breast at the bounce-up position, which is related to both the fabric recovery property and the body speed.

![Diagram of a woman's body with a bra](image)

(a) Initial

(b) Breast falling

(c) Breast bounce

Fig. 5 Bounce process of the breast in the body movement

To illustrate the dynamic deformation of the human body during the movement, we take three nodes (A, B, C) on the human body as examples to record the displacement changes. As shown in Figure 5(a), node A is at the shoulder, B at upper part of the breast and C at lower part of the breast. Corresponding to the positions of the three nodes, we also select three nodes on the bra denoted as A1, B1, C1, respectively.

![Diagram of breast deformation](image)

(a) Breasts

(b) Bra

Fig. 6 Displacements distribution in the position of breast falling

During the dynamic deformation, the displacements of the body vary along with the body parts. As an example, Figure 6 shows the displacement distributions of the breast and the bra at the position of 5(b). The scale in the figures is presented in unit of m, which can be transformed into unit of mm by multiplying 10^3. The figures illustrate that the displacements do not distribute uniformly over both breast and the bra in the body movement. The positive values of y-direction (darker contours) are observed over the areas of the human body shown in Figure 6(a) and the most area of the bra especially at shoulder strap shown in Figure 6(b), illustrating the going up movement of the body and the bra. The negative displacement against y-direction (marked as brighter contour) occurs at the breast and the lower part of the bra, indicating the bra stretches to conform the breast falling.

4.2 Mechanical behavior of the bra

4.2.1 The displacement of the bra

Bra will accommodate the breast deformation by fabric stretch and recovery. Figure 7 shows the bra displacement of three nodes (A1, B1, C1). For node A1 at the shoulder strap, the displacement appears increasing linearly with the body movement until reaching a level of steady slow increase. For the nodes B1, C1, the displacements are zero in the initial stage of the body movement, which is related to the bra accommodation to the upward movement of the body. The downward movement of the breast and the space allowance between the breast and the bra. Then, the displacement of node B1 is gradually increasing for accommodating the displacement of node B of
the breast. The displacement of node C_1 is decreasing to -1.8 mm then recovery to zero value, indicating the stretch and recovery property of the bra in accommodating the bouncing process of node C of the breast.

![Displacement diagram](image)

**Fig.7 Bra displacement at three nodes in y-direction**

<table>
<thead>
<tr>
<th>Node</th>
<th>Y Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_1</td>
<td>0.010000</td>
</tr>
<tr>
<td>B_1</td>
<td>0.008000</td>
</tr>
<tr>
<td>C_1</td>
<td>1.000000</td>
</tr>
</tbody>
</table>

**Fig.8 Displacement of the shoulder strap in x-direction**

Figure 8 shows the bra displacement of two nodes (at A position of right and left shoulder) in the shoulder straps x-direction. One positive value and one negative value in x-direction means that the shoulder straps of the bra is slipping on the skin surface during the movement of the body. In the initial stage of the body movement, the displacements of the two nodes are zero, indicating that no slipping occurs between the bra and the shoulder. Comparing them with the displacement in y-direction of node A_1, we find that the slippage is a factor causing the slow displacement in the final stage of the movement as shown in Figure 7.

4.2.2 Bra pressure

The stretch of the bra in multi-directions induces the pressure on the human body. Figure 9 shows the pressure distributions of the bra in two cases: (a) for the case of the breast falling and (b) for the case of the breast bouncing. The scale in the figures is presented in unit of kg/m², which can be transformed into unit of gf/cm² by multiplying 10⁻¹².

![Pressure distribution](image)

**Fig. 9 Pressure distribution of the bra**

Meanwhile, the negative value of pressure indicates the pressure on the body induced by the bra. The positive value of pressure indicates the force in the bra to move it towards the skin when the bra does not contact the body at a specific point. From the pressure contour plot, we can see that the pressure does not distribute uniformly over different parts of the bra. The pressure on most of the areas is in the range of 4 to 20gf/cm². When the breast is falling as shown Figure 9(a), high-pressure zones are observed in the lower part of the bra with a value of about 14gf/cm². When the breast is bouncing as shown in Figure 9(b), high-pressure zones are observed in the upper part of the bra with a value of about 20gf/cm².

4.2.3 Bra stress

Garment pressure is related to the strain-stress in the deformed fabric [12]. The effective stress is a scalar by
integrating all the internal stress components, such as tension, shearing and bending [1], which are shown as the positive values in the figures. Figure 10 represents the distributions of effective stress in the bra in two cases: (a) for the case of the breast falling and (b) for the case of the breast bouncing. The distributions of the effective stress have similar patterns in the contour plots of the bra pressure shown in Figures 9. The results suggest that the garment pressure distributions be directly related to the effective stress distributions in the garments. The effective stresses in the bra vary from 0 to 12 g/cm² in Figure 10(a), while those in Figure 10(b) vary in the range of 0 to 20 g/cm². For the three nodes, the maximum value is observed at node A1 with 18.7 g/cm², followed by node B1 and C1, indicating that the front straps are subject to the maximum strain-stress in vertical direction.

![Stress distribution of the bra](image)

4.3 Mechanical behavior of the breast

Responding to the dynamic movement and the bra pressure, there are stress-strain distributions in the breast. Figure 11 shows the distributions of effective stress in the breast during wearing the bra, (a) for the case of breast falling and (b) for the case of the breast bouncing. The contour plots show the stress distribution from zero value (bright color) to a positive value (dark color). The darker the color, the higher the stress value is. In Figure 11(a) of the breast falling, higher value of stress is observed in the root area around the breast. In Figure 11(b) of the breast bouncing, higher value of stress appears at the upper area of the breast. Many of the areas with effective stress about value of 1000 g/cm² are observed.

![Stress distribution of breast during the body movement](image)

(b) Breast bounce

Fig. 11 Stress distribution of breast during the body movement

5. Validation of the model

To validate the model, we compare the simulation results with the measurements from the experimental measurements of bra pressure reported by Makabe et al. [5]. In their experiment, pressures were measured at 6 points under the bras that have four styles and different material compositions. We select 6 points on the simulation model as shown in Figure 12, which correspond to the points used in the experiment: point a under bust line and mammary line cross, b under bust line and anterior axially line cross (seam), c under bust line and scapular line cross, d at the lateral area of cup and ribcageband cross, e at ribcageband and anterior axially line cross (seam), f at strap and shoulder line cross.

Figure 13 shows the comparison of the simulation results with the experimental measurements at the six points. Where the mean value of the four samples is used as the experimental values that have two classifications of the maximum pressure and minimum pressure.
measured. The simulated values are the values of the six points as breast bouncing as shown in Figure 9(b).

Fig. 12 The points corresponding to Makabe’s experiment

![Graph showing bra pressure measurements](image)

Fig. 13 Comparison of bra pressure between the prediction and the experiment

![Graph comparing bra pressure](image)

Fig. 14 Pressure changes of the six measuring points at the bra

The corresponding pressure changes are shown in Figure 14. For the points of d, e and f at the lateral area of cup and strap of bra, good agreement is observed between the simulation and the experiment. For the points of a, b and c that are all at underbust line, the simulated values appear to be much smaller than the experimental measurements. The major reason causing the deviation is due to the difference in bra-styles used in the experiment and in the simulation. In Makabe’s experiment, the bra had very tight-fitting style with stiff ring along underbust line, while in current numerical model, we can only simulate the style of one-piece sportsbra. Therefore, the pressure under the underbust line is predicted to be small. The prediction of bra pressure at the upper parts of the bra is close to the magnitude of the measurements from the experiments of bra pressure, indicating that the model is able to predict and simulate bra pressure during wear with reasonable accuracy.

6. Conclusion

A 3D bio-mechanical model of a female body, which consists of elastic breast and rigid body, has been developed on the basis of analyzing the bio-mechanical characteristics of human body. Bra is regarded as material linearity and geometric non-linearity. The contact between human body and bra is modeled as dynamic sliding interface based on the theory of contact mechanics. Finite element method is used in the time domain for deriving numerical solution of the dynamic contact problem.

An example is presented to illustrate the simulation results of the computational model: a female human model is walking at a constant speed when wearing a bra. The computational model can simulate and characterize the dynamical mechanical behavior of the breast and bra during the body movement with the breast falling and bouncing in terms of bra deformation, pressure and stress distributions and breast stress distributions. With the distributions of the variables, we can study the effects of bra on the dynamic deformation of the breast during the body movement. Comparing with the quantity of measured garment pressure reported in the literature, the predicted pressure is close to the magnitude of experimental measurements, indicating that the model is able to simulate bra pressure during wear with reasonable accuracy. The model can be used as an engineering design tool for optimizing the structure and material in bra design process.

ACKNOWLEDGEMENT

We would like to thank the Hong Kong Polytechnic University for the funding of this research through the Area of Strategic Development in Fashion Design and Technology Innovation with projects A188 and G-YW35.

References to literature
