This is an Accepted Manuscript of an article published by Taylor & Francis in International Journal of Fashion Design,Technology and Education on 2020-05-18 (published online), available at: http://www.tandfonline.com/10.1080/17543266.2020.1762249.

Soft manikin as tool to evaluate bra features and pressure

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Accurate evaluations of the interface pressure between the bra and skin are critically important prerequisites for the ergonomic design of bra components. Nevertheless, previous analyses on contact pressure have mainly relied on human wear trials with low data repeatability. Determining suitable pressure and tension of shoulder strap and underband to provide adequate breast support has been largely empirical. In this study, a manikin with breast prostheses is designed for bra pressure evaluation. The Novel Pliance-X® pressure system is used to measure the contact pressure induced by the underwire, shoulder straps, underband and different bra cup materials. The results demonstrate that the bra-manikin pressure is increased with a rigid shoulder strap and bra band, as well as flexible bra cup material and underwire. The manikin with breast prostheses shows a satisfactory result validated by a subject wear trial, thus providing a more reliable and objective approach for future bra studies.

Key word: bra features, bra material properties, bra-manikin pressure, soft manikin

1. Introduction

Female breasts have a soft structure, and therefore, are anatomically supported by the ligaments and skin (Zhou, Yu & Ng, 2011). Bras have been designed as a form of external support of the breasts to minimize motion of the breast tissues due to excessive motion (Bowles, Steele, & Munro, 2008). However, poorly fitting bras with tight shoulder straps, incorrect bra band tension and uncomfortable underwire to support the breast mass may lead to a poor fit, bra displacement, breast pain and skin rash under the underwire. Increased of compression forces from the bra may also result in increased interface pressure between the skin of the user and bra materials (Lu, Qiu, Wang, & Dai, 2016). Understanding of the bra design features with the pressure exerted onto the body provides bra designers with insight into the material properties and design parameters for less compression and therefore optimal comfort and support.

With previous research, the bra shoulder straps, centre of the underwire and bra band are in close contact with the skin and maintain the position of the bra (Yip & Yu, 2006; Liu, Istook, Liu, & Wang, 2017; Makabe, Momota, Mitsuno, & Ueda, 1991; Wang, Chen, & Lin, 2011). The material commonly used in bra shoulder strap and bra band is elastic tape which offers a certain degree of elasticity so that the wearer can breathe naturally (Coltman, McGhee, & Steele, 2015; Zheng, Yu, & Fan, 2008). The shoulder straps should be wider and have more cushioning for increased comfort (Bowles, et al., 2008). Wider shoulder straps increase the contact surface which allows the even distribution of pressure (Zhang, Li, Yeung, Yao, & Kong, 2000). Extension of the shoulder straps that affected by the elastic modulus along the strap or extended length of the bra band also affect the bra fit adjustment and the pressure comfort (Yip, 2016). On the other hand, over 80% of the breast weight is supported by the bra band

(Van Jonsson, 2013). The bra band should be fully stretched in order to resist the downward gravity forces especially for larger breasts (Chan, Yu, & Newton, 2015).

Bra cups are crucial for breast support with large contact area between the bra cup and breasts. Jung and Na (2016) examined the variations in the shape of the bra cups with a sensory test on bra cup fit and perceived comfort. Jeong et al. (2012) found that an inappropriate cup size may lead to free movement within the breasts or extra during wear. Bra cups can be fabricated from a wide range of materials such as polyurethane foam which offers a large variety of rigidity and thickness with the ability to absorb shocks (Gnanasundaram, Durairaj, Gopalakrishna, & Das, 2013). Nevertheless, there has been limited work on the stress-strain of the bra cup material and its effects on breast compression and wear comfort.

In pressure and comfort evaluation of bra features, the interface pressure between the bra and skin and the contact conditions has been traditionally measured by using pressure measurement equipment (Steele, 2013). A study on the pressure comfort of elastic sports vest by Liu, Chen, Wei, and Pan (2013) indicated that a comfortable pressure exerted onto the body ranges from 0.96 to 1.35 kPa. Coltman et al. (2015) found that a pressure of 4.9 kPa from wearing a cross-back bra results in a higher discomfort score compare with straight orientation. Nevertheless, the mean pressure that is imposed onto the human body from a bra greatly varies due to movement, posture and even deep breathing, as well as the anatomic location of the sensors of the pressure measurement system. The use of wear trials to measure the bra-skin pressure that involve human subjects therefore results in low repeatability of the testing (Wang, Chen & Lin, 2011; Wong, Li & Zhang, 2004). Moreover, the sample size is usually small which fails to address the large variances in breast characteristics such as tissue composition and shape even for women who have the same bra size (Liu Miao, Dong & Xu, 2018).

In considering the uncontrollable and unavoidable noise from the evaluation of comfort with human subjects, human manikins and 3D biomechanical mathematical models have been developed to predict and investigate pressure performances of bra features (Nayak & Padhye, 2017; Fan & Chan, 2005; Wettenschwiler et al., 2017; Chang, Gao, & Yan, 2009; Haake & Scurr, 2010; Page & Steele, 1999; Starr et al., 2005; Yanmei, Weiwei, Fan, & Qingyun, 2014; Ying, Wang, Liu, & Zhang, 2011). Due to the lack of information on the human soft tissues, traditional manikins and mathematic modelling approach in previous biomechanical analyses of bra-breast contact pressure were generally assumed to be rigid and incompressible, which adversely affects the accuracy and reliability of the garment pressure results. Artificial mannequin systems consist of a soft surface to cover the rigid internal section have been introduced for evaluation of contact pressure (Fan & Chen, 2002; Yu, Fan, Ng, & Gu, 2006; Wang et al., 2011). However, due to unverified parameters of the surface of the skin, the manikins are not intended for comfort and pressure evaluations of intimate apparel. The relationship between pressure and bra design features has not yet been reported. The effects of the bra design modifications and material property changes towards the bra-skin pressure is not well understood through the traditional approaches of pressure evaluation. This study therefore proposes a more reliable approach to maintain consistent testing conditions for bra-manikin pressure evaluations by using a manikin with breast prostheses. Hence, the influence of bra design and material parameters on pressure and wear comfort can be systematically investigated, providing reliable guidelines to advance the bra design and development process.

2. Methods

2.1 Test bra

A changeable wired bra design that allows adjustment of tension or replacement of the bra components such as changing the shoulder straps and removing the underwire in a flexible manner is used (Luk, Yu, Liu, & Suh, 2015) (Figure 1). The length of the shoulder strap and bra band can also be adjusted by using the sliders during the experiment so that the effect of different material properties on the bra-manikin pressure can be systematically evaluated.

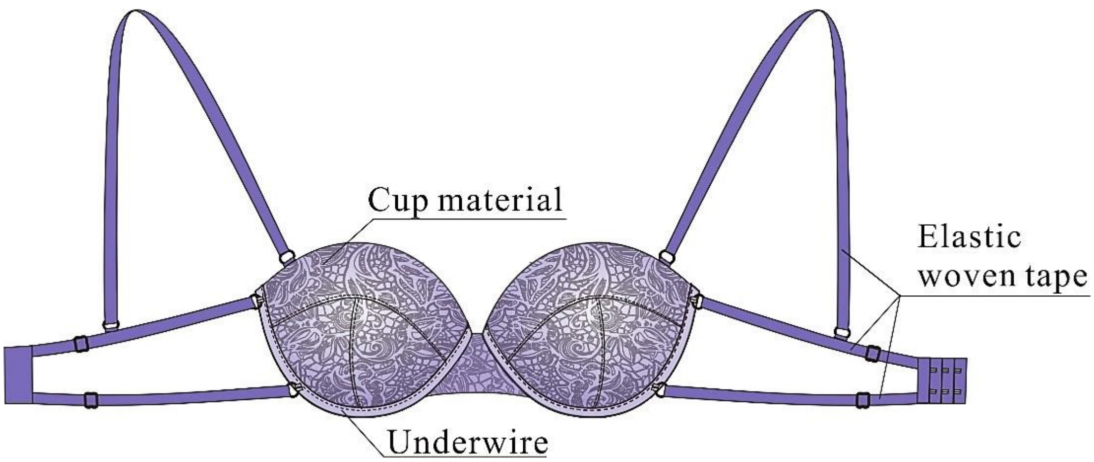

Figure 1. Changeable bra

In this study, two types of elastic woven tapes are used for the shoulder strap and bra band, namely EW1 (100% polyester) and EW2 (100% nylon tricot), respectively. Both woven tapes are 1.2 cm (in width) and 2.5 mm (in thickness), whilst the shoulder straps are aligned in a straight orientation. Following the standard test method for tension and elongation of the elastic fabrics (ASTM D4964), an Instron 4411 tensile strength tester (Norwood, MA, USA) was used to measure the stress-strain behaviour of the material. The narrow elastic samples sewn into a loop shape that loads at 30%, 50% and 70% tension strains were measured for calculating the Young's modulus of the material.

Two types of textile materials commonly used for the bra cups were sourced from the commercial market: CM1 and CM2. CM1 is lace with a warp knitted structure, whilst CM2 is a fabric-foam laminate which consists of polyurethance (PU) foam and nylon (Table 1). To assess the effect of the properties of the cup materials on the bra-skin pressure, the Standard Test Method for Stretch Properties of Textile Fabrics – CRE Method (ASTM S6614) was used along with the Instron 4411 tensile strength tester (Norwood, MA, USA).

Table 1. Material specifications of tested cup materials

Cup material	Material structure	Thickness (mm)	Weight (g/m^2)
CM1	Lace in warp knitted structure	0.83	90.5
CM2	Fabric-foam laminate	4.25	287.0

2.2 Manikin with breast prostheses

To evaluate the amount of pressure exerted by different bra components and/or materials onto the body, a manikin with breast prostheses was designed and developed to replace human subjects in bra fitting trials (Figure 2). The physical body dimensions and properties of the soft manikin were developed with reference to the upper part of a female body with underbreast circumference of 75 cm. A soft artificial layer of skin made with silicone material which many clinical research studies have used and considered to be similar to the texture of human skin was used (Derler, Spierings, & Schmitt, 2005; Parmar, Khodasevych, & Troynikov, 2017). The artificial skin has a certain softness and flexibility so it can simulate real human skin well, and enclose the breast tissues. As for the elasticity (Gefen & Dilmoney, 2007; Hsu, Palmeri, Segars, Veress, & Dobbins III, 2011; Serup, Jemec, & Grove, 2006), the thickness, Shore hardness, density and elastic modulus of the artificial skin layer are 10 mm, 19.2, 1063.9 kg/m^3 and 259.7 kPa respectively. With reference to the breast size of subjects recruited in this study, two pairs of commercial breast prostheses (in cup sizes of B and D) sourced from Trulife Breastcare (clinical breast company) which have mechanical properties that approximate those of the soft-tissues of human breasts were inserted into the manikin. Additional B cup breast prostheses are also used to collect the bra-manikin pressure result and compare with the wear trial results.

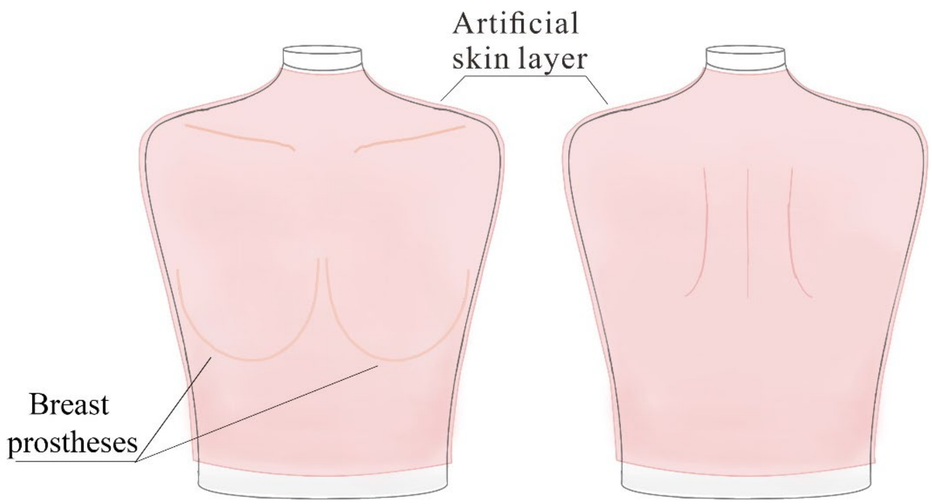

Figure 2. Manikin with breast prostheses

2.3 Pressure measurement

Based on the dimensions of the manikin with breast prostheses, a total of four changeable bras were custom-made with elastic woven tape, EW1 and EW2, bra cup materials CM1 and CM2, and underwire for support for this study (Table 2). The influence of the material tensile behaviour and length adjustments (tension changes) on the interfacial pressure delivered to the wearers was systematically investigated.

Table 2. Bra conditions

Bra Condition	Cup material	Shoulder strap and underband	Underwire
Control	CM1	EW1	Yes
X	CM1	EW2	Yes
Y	CM2	EW1	Yes
Z	CM1	EW1	No

The Novel Pliance-X® pressure system, which has been validated for measuring interfacial pressure exerted by garments onto a soft body, was used to measure the bra-manikin pressure by placing the sensor between the skin and the bra components (Zhang, Yeung, & Li, 2002; Zheng, Yu, & Fan, 2009). The strip sensor used was 10 mm in diameter (in contact area of 78.54 mm^2) and 0.95 mm in thickness. A non-sensing extended conductive strip was used, which allows insertion into the desired measurement points. This is a capacitive sensor with a sensing pressure that ranges from 0.5 to 60 kPa; the experimental error was proven to be less than 0.13 kPa. There is high linearity between the applied pressure and sensor outputs and good repeatability with coefficients of variation less than 0.1 kPa (Ng, Au, Zhou, & Yu, 2008). As shown in Figure 3, interfacial pressure measurements are taken at three different locations including mid-point of underwire, shoulder and underband at the back, which are common sites for bra-skin pressure analysis because of the bony prominence of the clavicle and rib cage (Chan et al., 2015; Wang, Chen, & Lin, 2011; Zheng, Yu, & Fan, 2009). The interfacial pressure was measured three times at each location and their mean values were calculated.

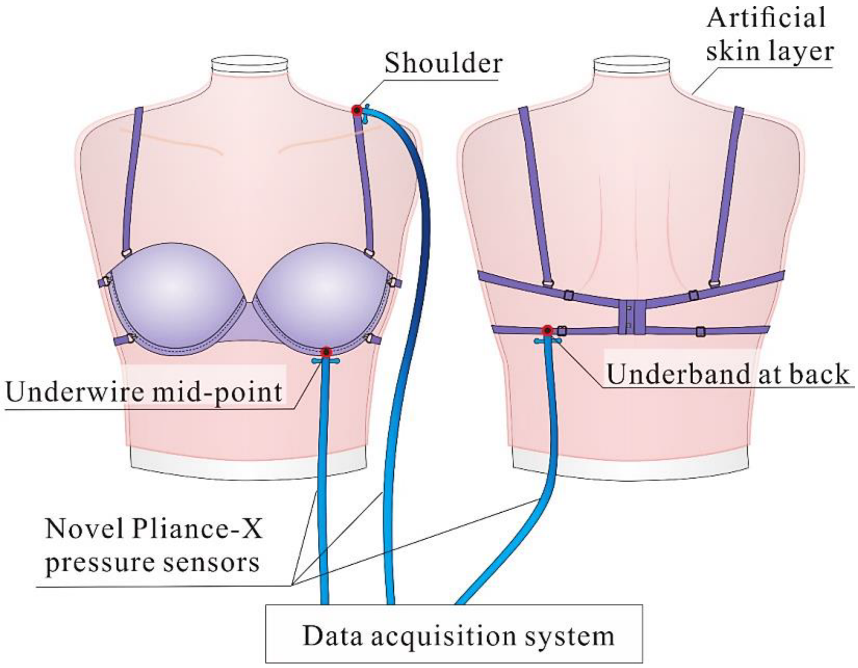

Figure 3. Bra-manikin pressure measured locations including mid-point of underwire, shoulder and underband at the back

The lengths of the shoulder strap and underband are vital because they affect the bra fit and comfort. Compression is induced by tension (from the length and stress-strain properties of the material) when the bra is stretched and worn. To obtain an appropriate bra fit, the recommendation is that the length of the underband has an ease of 10 cm for an underbust girth of 75 cm (Shin, 2007). With the help of a professional bra fitter, a shoulder strap length of 40 cm has been identified to provide the optimum fit for this manikin based on a fitting trial test from McGhee & Steele's study (2010) with adjustment or selection on shoulder strap, underband, bra cup and underwire. To evaluate the influence of tension changes in the shoulder straps and underband on bra-skin pressure, a total of fifteen tension conditions along with five underband lengths (65 cm, 69 cm, 73 cm, 77 cm and 81 cm) and three shoulder strap lengths (38 cm, 40 cm and 42 cm) were used for each bra condition (Table 3). Each test was repeated five times to examine the repeatability of the test method.

Table 3. Tension conditions of different shoulder strap and underband lengths

Tension code (length of underband)	Tension code (length of shoulder strap)		
	I (38 cm)	II (40 cm)	III (42 cm)
A (65 cm)	IA	IIA	IIIA
B (69 cm)	IB	IIB	IIIB
C (73 cm)	IC	IIC	IIIC
D (77 cm)	ID	IID	IIID
E (81 cm)	IE	IIE	IIIE

A correlation analysis was conducted with Statistical Package of Social Science (SPSS) in which the major factors that affect the bra-manikin pressure are identified. Six independent variables were analysed, including the length of the shoulder strap and underband, and stress-strain behaviour of the bra cup, shoulder strap and underband material and underwire. These variables can affect bra fit and it is beneficial to understand their effect on pressure in particular measured points.

2.4 Pressure measurement validation and statistical analysis

To examine the representativeness of the bra-manikin pressure result with the use of the manikin with breast prostheses, a wear trial was carried out for validation purposes. Five female subjects with bra size of 75B/D with no prior history of breast injury or surgery were recruited. The experimental process was approved by the Human Subjects Ethics Sub-committee at The Hong Kong Polytechnic University. Written consent was obtained after providing information on the wear trial procedures to the subject. They had to wear the control bra (fabricated with EW1 and CM1, and an underwire for support) in which bra-manikin pressure measurements at the mid-point of underwire, underband and shoulder were taken. The collected results of the bra-manikin pressure values of the subject from the wear trial were compared with those of the manikin with breast prostheses. A correlation analysis was used to determine the relationship between the bra-manikin pressures and the bra-skin pressures. The root mean square error of pressures recorded at mid-point of underwire, shoulder strap and underband were calculated to present the discrepancies. Upon examination, the Pearson correlation coefficients could reflect the strength of the linear relationship between the bra-manikin pressures and the bra-skin pressures at various measuring locations.

3. Results

3.1 Material properties

To understand the effects of the material parameters on the bra-skin pressure, the stress-strain behaviour of the elastic woven tapes (EW1 and EW2) and the cup materials (CM1 and CM2) was first measured. The stress-strain behaviour of EW1 and EW2 is presented in Figure 4. The Young's modulus of the materials which is commonly used to characterize material elasticity is calculated and the results are shown in Table 4. In comparison to EW1 which has a lower modulus of 9.86 MPa, EW2 has a higher Young's modulus of 15.58 MPa which means that it is more rigid and less stretchable. CM2 has a higher modulus (stretches less) in both the wale and course directions as compared to CM1.

Table 4. Young's modulus of tested elastic woven tapes and cup materials

Material	Course direction (E_1)	Wale direction (E_2)
EW1	9.86 MPa	
EW2	15.58 MPa	
CM1	0.33 MPa	0.33 MPa
CM2	0.18 MPa	0.28 MPa

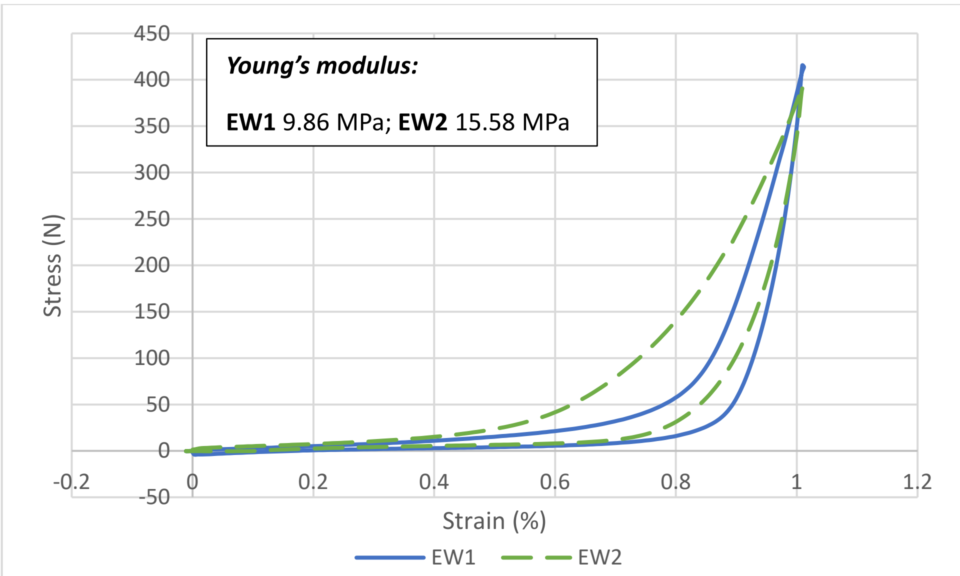

Figure 4. Stress-strain behaviour of elastic woven tapes

3.2 Validation

It can be seen that the correlation coefficients for the relationships between the bra-manikin pressure and bra-skin pressure on the three measured points are ranged from 0.782 to 0.861 (n=75, p<0.01(two-tailed)) which indicate that they are highly positively correlated with one another. In order to understand the discrepancies between measuring method with human subjects and manikin with breast prostheses, the root mean square error (RMSE) was calculated between bra-skin pressure and bra-manikin pressure at the three measured locations respectively. Results indicated that the pressure differences at shoulder strap, underband and underwire (mid-point) are satisfactory, the values of RMSE are 0.94 kPa, 1.47 kPa and 2.17 kPa respectively. Amongst the 3 pressure measuring locations, the differences obtained at mid-point of underwire are relatively large which may be attributed to the complex shape geometry of the breasts which vary from individual to individual, affecting the fit of underwires and the corresponding bra-skin pressure. The repeatability of the bra-manikin pressure measurements has also been evaluated. The coefficient of variation (CV) for the bra-manikin pressure measurement of the manikin with breast prostheses is generally less than 2%. The results demonstrated that this method is repeatable with consistent result.

3.3 Bra-manikin interfacial pressure and bra strain

The use of a manikin with breast prostheses allowed the influence of the bra features and material properties on bra-manikin pressure at the underbreast and back bodice as well as on the shoulder to be systematically investigated. Table 5 presents the bra-manikin pressure measurements with changes in the material and length of the shoulder strap and underband, and underwire for four bra conditions. The results show that a change in the length of the shoulder straps and underband, the material properties and insertion of underwires have a major effect on the amount of bra-skin pressure.

Table 5. Bra-manikin pressure in different bra conditions

Pressure (kPa)	Condition	IA	IIA	IIIA	IB	IIB	IIIB	IC	IIC	IIIC	ID	IID	IIID	IE	IIE	IIIE
Shoulder strap length		38 cm	40 cm	42 cm	38 cm	40 cm	42 cm	38 cm	40 cm	42 cm	38 cm	40 cm	42 cm	38 cm	40 cm	42 cm
Underband length		65 cm			69 cm			73 cm			77 cm			81 cm		
1.Mid-point of underwire	Control	10.6	10.6	10.6	10.4	10.4	10.3	9.8	7.9	7.5	8.2	7.6	6.8	7.3	7.1	5.9
	X*	10.6	10.6	10.6	10.6	10.5	10.4	10.3	10.1	9.8	9.7	9.5	9.3	8.5	7.9	7.2
	Y*	10.6	10.6	10.6	10.5	10.4	10.4	10.2	9.9	9.8	9.7	9.5	9.1	8.4	7.8	7.3
	Z*	6.3	5.8	4.6	5.6	4.6	3.0	4.5	3.6	2.4	3.3	2.2	2.1	1.8	1.5	1.5
2. Shoulder	Control	8.0	6.6	5.4	6.8	5.9	5.3	7.1	6.3	4.8	6.5	4.4	3.3	5.5	3.7	2.6
	X*	9.3	8.6	7.7	8.6	8.2	7.8	8.8	8.4	6.5	7.2	6.6	5.8	6.7	5.7	4.8
	Y	8.5	7.4	5.8	7.0	6.4	5.6	7.5	6.6	5.3	6.9	4.8	3.7	6.1	4.3	2.9
	Z	7.8	7.0	6.5	6.7	5.8	5.4	6.9	6.2	5.1	6.2	4.6	3.5	5.3	3.4	2.7
3. Underband at back	Control	7.3	6.5	6.2	5.3	5.2	5.5	4.4	4.3	3.8	1.7	1.7	1.6	0.6	0.6	0.5
	X*	8.5	8.2	7.7	7.2	6.6	5.8	5.4	5.3	4.6	4.2	4.1	4.0	3.5	2.8	1.8
	Y*	8.0	7.8	7.3	6.8	6.2	5.5	5.2	5.0	4.3	3.7	4.2	3.8	2.6	2.3	1.5
	Z	7.0	6.1	5.8	4.9	4.7	5.0	4.2	3.8	3.5	2.0	1.8	1.5	1.2	0.6	0.4

Remarks: Conditions I, II and III refer to shoulder strap lengths of 38 cm, 40 cm and 42 cm while A, B, C, D and E refer to underband lengths of 65 cm, 69 cm, 73 cm, 77 cm and 81 cm respectively. * represents pressure has significant differences compared to Control condition (p-value < 0.05).

In the control condition, in which the underband was fixed at the best fitting length of 65 cm, the pressure measured at the shoulder ranges from 5.4 kPa to 8.0 kPa (tension conditions IA, IIA and IIIA). A longer length of the underband not only leads to reduced bra-manikin pressure on the torso at the mid-point of underwire and underband at the back, but also causes a slight increase in pressure on the shoulders significantly (p-value < 0.05).

The material properties of the shoulder strap, underband and bra cup, as well as the underwire in relation to the bra-manikin pressure were further investigated. Changing the elastic material provides similar bra-manikin pressure results under various tension conditions. Nevertheless, there is a consistently significant higher pressure of 0.5 kPa to 2 kPa noted on the three measured points as opposed to the control sample with Bra Condition X (p-value < 0.05). The use of EW2, a rigid elastic woven tape, resulted in higher bra-manikin pressure values as compared to EW1, a highly stretchable elastic tape.

The impact of a soft flexible fabric-foam laminate cup material in Bra Condition Y on the bra-skin interfacial pressure was further investigated. The soft cup material of Bra Condition Y causes a significant small bra-manikin pressure increase at the torso (mid-point of underwire and underband at the back) as compared to the control sample (p-value < 0.05).

In this study, the absence of an underwire in Bra Condition Z results in a substantial decrease of the bra-manikin pressure at the middle of the under breast curve of 39% to 79% with various tension conditions of the shoulder straps and underband significantly (p-value < 0.05). With the tightest shoulder strap and underwire with the highest tension (IA), the pressure obtained at the mid-point of underwire is observed to be highest (10.6 kPa) in the control sample, whilst a lower pressure of 6.3 kPa is found in Bra Condition Z. When the underband is fixed at the best fitting length of 65 cm, a high pressure of 5.8 kPa to 7.8 kPa was induced by the shoulder straps and underband, respectively.

A correlation analysis was then conducted. The independent variables of the underband length, stress-strain behaviour of the bra cup material, shoulder strap and underband material, and underwire show significantly linear relationships with the bra-manikin pressure at the mid-point of underwire (p-value < 0.05). The influence of the length of the shoulder strap and underband, and the stress-strain property of the elastic woven tape on pressure exerted onto the shoulders is statistically significant (p-value < 0.05).

4. Discussion

As compared to subjects with large variances in breast characteristics, posture changes and the rate of breathing during the experiment that affect the outcomes and repeatability of the testing, the manikin with breast prostheses and an artificial layer of skin maintains consistent testing conditions for the bra pressure evaluation. The correlation result also assists to demonstrate the case with a previous report on human subjects (Chen et al. 2016), the shoulder strap, bra band, cup material and underwire are the critical bra components that impact the bra-manikin pressure and related bra discomfort.

The range of the bra-manikin pressure (5.8 kPa to 10.6 kPa for the best fitting bra condition, IIA) based on the manikin with breast prostheses well aligns with those of previous studies in that a high induced pressure of 5.2 kPa to 10.6 kPa and 6.2 kPa to 13.8 kPa are due to the shoulder straps and underband respectively (Bowles & Steele, 2013; Coltman et al. 2015).

An excessively high amount of pressure (10.6 kPa) was recorded at the mid-point of underwire for the best fitting length of the underband regardless of the material properties, length or tension of shoulder straps. Increasing the length of the shoulder straps and the underband in turn increases bra gapping and reduces the bra-skin pressure. However, in doing so, this may affect the original fit of the bra and the intended protection and support to the breasts.

Regarding to adjust a longer length in underband lower pressure on other measured points but slight increase on shoulder position, it is anticipated that when a loosened bra band fails to bear the mass of the breasts, the force may be transferred to the shoulders to hold the breasts in place. Since forces induced by the weight of the breasts are somewhat retained at the middle of the underwire with a good-fitting underband, there are high pressure at that point. Therefore, the designers or developers are discovered for advanced design for underwire and searching for different materials to redistribute the pressure to balance the support function and wearing comfort (Martinet & Yip, 2013; Morris, 2014).

Rigid shoulder strap or underband are commonly used for compression sports bras to prevent excessive breast motion during exercise inevitably result in exerting a high amount of pressure onto the skin (Li, Zhang, & Yeung, 2003). Bowles, Steele and Munro (2012) indicated that rigid materials can also support a large breast volume and reduce the gradual loss of tension and distortion of material over time with use. Hence, bra straps that comprise two degrees of modulus and elongation have been developed recently (Yu, 2016). A low modulus and high elongation material is used as the front section to maintain the bra comfort while the support function of the bra is preserved with the high modulus and material with less elongation in the back section. On the other hand, a wider shoulder strap or underband increases the contact area and contributes to a more even pressure distribution (Zhou & Yu, 2013). This would reduce discomfort due to a high pressure at a single point (Yu, 2016).

The underwire is one of the most prevalently found bra components that is inserted into the bottom rim of the bra cup material and carries the weight of the breasts as well as helps to lift up the breasts (Chan et al., 2015). Traditional planar underwire require the stretch force from shoulder strap and bra band and transform to 3D shape to fit the breast contour (Liu et al., 2017). It should be noted that incorrect adjustment of the shoulder straps and underband may cause gapping and a poor underwire fit. This would cause a wear discomfort and even pain. Although pressure is reduced by removing the underwire, it is not suggested to remove to prevent scarifying the support function. Instead, innovative design of underwire with soft end or 3D shape are developed to improve the underwire perceived comfort (Cheung, 2014; Martinet & Yip, 2013).

5. Conclusions

This study uses a novel manikin with breast prostheses to evaluate the bra-manikin pressure with different bra features and materials. The bra-skin interfacial pressure results of the manikin with breast prostheses are in a good agreement with the wear trial results obtained from a human subject. The use of the manikin can therefore effectively eliminate the variations in individual wear trials in that the influence of the bra design features and material properties in relation to the induced pressure onto the body and the corresponding wear comfort can be systematically studied. As a result, bra designers can benefit from utilizing the manikin with breast prostheses in the bra design process with an appropriate selection of materials. The results indicate that the high stress-strain behaviour of the shoulder strap, and bra band and flexible bra cup materials results in high bra-manikin pressure due to increase in the compression and tension forces. To enhance bra comfort, the elastic material properties of the shoulder strap and underband together with their corresponding lengths in pattern development should be well balanced for an optimum fit and pressure distribution. With improved bra fit, the bra can reduce the excessive stress caused by the mass of the breasts and strategically distribute the pressure to the shoulders, bottom of the breasts and underband with satisfactory bra comfort. Although a satisfactory result is obtained from the manikin with breast prostheses, it is recommended that more subjects are included to validate the result due to individual variations in breast shape and properties. With the use of a manikin with breast prostheses, further studies on more typical bra features or styles are advised to enhance the consistency and reliability of bra evaluation.

Acknowledgment

We acknowledge financial support from the Research Grant Council for this research project through project account PolyU 152375/16E and the Central Research Grant support to account PolyU 152089/15E.

References

Bowles, K. A., & Steele, J. R. (2013). Effects of strap cushions and strap orientation on comfort and sports bra performance. *Medicine and Science in Sports and Exercise, 45*(6), pp. 1113-1119. doi:10.1249/MSS.0b013e3182808a21 Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/23274596

Bowles, K. A., Steele, J. R., & Munro, B. (2008). What are the breast support choices of Australian women during physical activity? *British Journal of Sports Medicine, 42*(8), pp. 670-673. doi:10.1136/bjsm.2008.046219 Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/18523041

Bowles, K. A., Steele, J. R., & Munro, B. J. (2012). Features of sports bras that deter their use by Australian women. *Journal of Sports Medicine, 15*(3), pp. 195-200. doi:10.1016/j.jsams.2011.11.248 Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/22188847

Chan, C. Y. C., Yu, W. W. M., & Newton, E. (2015). Evaluation and Analysis of Bra Design. *The Design Journal, 4*(3), pp. 33-40. doi:10.2752/146069201789389601

Chang, L. X., Gao, W.-D., & Yan, X. L. (2009). Studies of sports bra based on biomorphic analyses of females breasts. Bioinformatics and Biomedical Engineering, 2009. ICBBE 2009. 3rd International Conference on.

Cheung, S. (2014). Three-Dimensional Bra Underwire. *U.S. Patent Application No. 12/942,764*. Washington, DC: U.S. Patent and Trademark Office.

Coltman, C. E., McGhee, D. E., & Steele, J. R. (2015). Bra strap orientations and designs to minimise bra strap discomfort and pressure during sport and exercise in women with large breasts. *Sports Medicine Open, 1*(1), p 21. doi:10.1186/s40798-015-0014-z Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/26284162

Derler, S., Spierings, A., & Schmitt, K.-U. (2005). Anatomical hip model for the mechanical testing of hip protectors. *Medical engineering & physics, 27*(6), pp. 475-485.

Fan, J., & Chan, A. (2005). Prediction of girdle's pressure on human body from the pressure measurement on a dummy. *International Journal of Clothing Science and Technology, 17*(1), pp. 6-12.

Fan, J., & Chen, Y. (2002). Measurement of clothing thermal insulation and moisture vapour resistance using a novel perspiring fabric thermal manikin. *Measurement Science and Technology, 13*(7), p 1115.

Gefen, A., & Dilmoney, B. (2007). Mechanics of the normal woman's breast. *Technology and Health Care, 15*(4), pp. 259-271.

Gnanasundaram, S., Durairaj, D., Gopalakrishna, G., & Das, B. (2013). PU viscoelastic memory foam for application as cushion insole/insock in shoes. *Footwear Science, 5*(sup1), pp. S22-S23.

Haake, S., & Scurr, J. (2010). A dynamic model of the breast during exercise. *Sports Engineering, 12*(4), pp. 189-197. doi:10.1007/s12283-010-0046-z

Holmér, I., & Nilsson, H. (1995). Heated manikins as a tool for evaluating clothing. *The Annals of Occupational Hygiene, 39*(6), pp. 809-818.

Hsu, C. M., Palmeri, M. L., Segars, W. P., Veress, A. I., & Dobbins III, J. T. (2011). An analysis of the mechanical parameters used for finite element compression of a high-resolution 3D breast phantom. *Medical physics, 38*(10), pp. 5756-5770.

Jeong, S. J., Lim, H. S., Lee, J. S., Park, M. H., Yoon, J. H., Park, J. G., & Kang, H. K. (2012). Medullary carcinoma of the breast: MRI findings. *American Journal of Roentgenology, 198*(5), pp. 482-487.

Jung, H. S., & Na, M. H. (2016). Development of a Water-Droplet-Shaped Bra Mold Cup Design. *Indian Journal of Science and Technology,* *9*(35)doi:10.17485/ijst/2016/v9i35/101765

Kang, M. H., Choi, J. Y., & Oh, J. S. (2015). Effects of Crossed Brassiere Straps on Pain, Range of Motion, and Electromyographic Activity of Scapular Upward Rotators in Women With Scapular Downward Rotation Syndrome. *PM R, 7*(12), pp. 1261-1268. doi:10.1016/j.pmrj.2015.05.016 Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/26032346

Li, Y., Zhang, X., & Yeung, K. (2003). A 3D biomechanical model for numerical simulation of dynamic mechanical interactions of bra and breast during wear. *Sen'i Gakkaishi, 59*(1), pp. 12-21.

Liu, C., Miao, F.-X., Dong, X.-Y., & Xu, B. (2018). Enhancing pressure comfort of a bra's under-band. *Textile Research Journal, 88*(19), pp. 2250-2257.

Liu, H., Chen, D., Wei, Q., & Pan, R. (2013). An investigation into the bust girth range of pressure comfort garment based on elastic sports vest. *Journal of the Textile Institute, 104*(2), pp. 223-230. doi:10.1080/00405000.2012.714940

Liu, Y., Istook, C. L., Liu, K., & Wang, J. (2017). Innovative method for creating fitted brassiere wire prototype based on transformation matrix algorithm. *The Journal of The Textile Institute*, pp. 1-6. doi:10.1080/00405000.2017.1326366

Lu, M., Qiu, J., Wang, G., & Dai, X. (2016). Mechanical analysis of breast–bra interaction for sports bra design. *Materials Today Communications, 6*, pp. 28-36. doi:10.1016/j.mtcomm.2015.11.005

Luk, S., Yu, W., Liu, L., & Suh, M. (2015). Exchangeable cup bridge connection system: State Intellectual Property office of the P.R.C.

Makabe, H., Momota, H., Mitsuno, T., & Ueda, K. (1991). A study of clothing pressure developed by the girdle. *Journal of the Japan Research Association for Textile End-Uses, 32*(9), pp. 424-438.

Martinet, N. M., & Yip, K. Y. (2013). *U.S. Patent No. 8,585,459*. Washington, DC: U.S.

Patent and Trademark Office.

McGhee, D. E., & Steele, J. R. (2010). Optimising breast support in female patients through correct bra fit. A cross-sectional study. *Journal of Science and Medicine in Sport, 13*(6), pp. 568-572. doi:10.1016/j.jsams.2010.03.003 Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/20451452

Mills, C., Risius, D., & Scurr, J. (2015). Breast motion asymmetry during running. *Journal of Sports Sciences, 33*(7), pp. 746-753. doi:10.1080/02640414.2014.962575 Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/25356791

Morris, D (2014). Bra Wire Technology. *Intimate Apparel Journal, 2*(1), 48-61.

Nayak, R., & Padhye, R. (2017). *Manikins for Textile Evaluation*: Woodhead Publishing.

Netscher, D. T., Meade, R. A., Goodman, C. M., Brehm, B. J., Friedman, J. D., & Thornby, J. (2000). Physical and psychosocial symptoms among 88 volunteer subjects compared with patients seeking plastic surgery procedures to the breast. *Plastic and Reconstructive Surgery, 105*(7), pp. 2366-2373.

Ng, S., Au, A., Zhou, J., & Yu, W. (2008). Measuring methods of bra pressure.

Page, K. A., & Steele, J. R. (1999). Breast motion and sports brassiere design. *Sports Medicine, 27*(4), pp. 205-211.

Parmar, S., Khodasevych, I., & Troynikov, O. (2017). Evaluation of flexible force sensors for pressure monitoring in treatment of chronic venous disorders. *Sensors, 17*(8), p 1923.

Serup, J., Jemec, G. B., & Grove, G. L. (2006). *Handbook of non-invasive methods and the skin*: CRC press.

Shin, K. (2007). Patternmaking for the underwired bra: New directions. *Journal of the Textile Institute, 98*(4), pp. 301-318. doi:10.1080/00405000701503006

Starr, C., Branson, D., Shehab, R., Farr, C., Ownbey, S., & Swinney, J. (2005).

Biomechanical analysis of a prototype sports bra. *Journal of Textile and Apparel, Technology and management, 4*(3), pp. 1-14.

Steele, J. R. (2013). *The biomechanics of better bras: improving support and comfort during exercise.* ISBS-Conference Proceedings Archive.

Van Jonsson, L. (2013). *The Anatomy of the Bra*. Laurie van Jonsson.

Wang, L., Chen, D., & Lin, B. (2011). Effects of side strap and elastic hems of bra materials on clothing pressure comfort. *Journal of Fiber Bioengineering and Informatics, 4*(2), pp. 187-198.

Wang, Y., Cui, Y., Zhang, P., Feng, X., Shen, J., & Xiong, Q. (2011). A smart mannequin system for the pressure performance evaluation of compression garments. *Textile research journal, 81*(11), pp. 1113-1123.

Wettenschwiler, P. D., Annaheim, S., Lorenzetti, S., Ferguson, S. J., Stämpfli, R., Psikuta, A., & Rossi, R. M. (2017). Validation of an instrumented dummy to assess mechanical aspects of discomfort during load carriage. *PloS one, 12*(6), p e0180069.

Wong, A. S., Li, Y., & Zhang, X. (2004). Influence of fabric mechanical property on clothing dynamic pressure distribution and pressure comfort on tight-fit sportswear. *Sen'i Gakkaishi, 60*(10), pp. 293-299

Yanmei, L., Weiwei, Z., Fan, J., & Qingyun, H. (2014). Study on clothing pressure distribution of calf based on finite element method. The Journal of The Textile Institute, 105(9), pp. 955-961. doi:10.1080/00405000.2013.865883

Ying, B., Wang, Y., Liu, F., & Zhang, X. (2011). Study on the definition of moulded bra cup features and parametric modeling. Textile Bioengineering and Informatics Symposium Proceedings.

Yip, J. (2016). Narrow fabric elastic tapes *Advances in Women's Intimate Apparel Technology* (pp. 25-35): Elsevier.

Yip, J., & Yu, W. (2006). *Intimate apparel with special functions*: Woodhead Publishing Limited, Cambridge

Yu, W. (2016). *Advances in Women's Intimate Apparel Technology*: Woodhead Publishing.

Yu, W., Fan, J., Ng, S., & Gu, H. (2006). *Female Torso Mannequins with Skeleton and Soft Tissue for Clothing Pressure Evaluation, In "Thermal Manikins and Modeling.* Sixth International Thermal Manikin and Modeling Meeting (613M),"(Fan, J., Ed.), The Hong Kong Polytechnic University, Hong Kong.

Zhang, X., Li, Y., Yeung, K., Yao, M., & Kong, L. (2000). *A finite element study of stress distribution in textiles with bagging, computational mechanics: techniques and developments.*

Zhang, X., Yeung, K., & Li, Y. (2002). Numerical simulation of 3D dynamic garment pressure. *Textile research journal, 72*(3), pp. 245-252.

Zheng, R., Yu, W., & Fan, J. (2008). Prediction of seamless knitted bra tension. *Fibers and Polymers, 9*(6), pp. 785-792.

Zheng, R., Yu, W., & Fan, J. (2009). Pressure evaluation of 3D seamless knitted bras and conventional wired bras. *Fibers and Polymers, 10*(1), pp. 124-131. doi:10.1007/s12221-009-0124-7

Zhou, J., & Yu, W. (2013). A Study on Biomechanical Models of Sports Bra's Shoulder Straps. *Journal of Fiber Bioengineering and Informatics, 6*(4), pp. 441-451.

Zhou, J., Yu, W., & Ng, S. P. (2011). Methods of studying breast motion in sports bras: a review. *Textile research journal*, *81*(12), 1234-1248.

Zhuo, W. L., Sheng, C. D., Wei, Q. F., & Bin, L. (2011). Effect of Elastic Materials on Pressure Comfort of Tight-Fit Bra. *Applied Mechanics and Materials, 79*, pp. 221-226. doi:10.4028/www.scientific.net/AMM.79.221