The elasticity distribution of under-band based on pressure comfort and breast support performance for seamless sports bras

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ABSTRACT – REZUMAT

The elasticity distribution of under-band based on pressure comfort and breast support performance for seamless sports bras

Seamless knitted sports bra is becoming popular for its high performance in tactility and pressure comfort, however, it also encounters the problem of insufficient support. To improve the support performance, it is always knitted with strong elastic material in a reduced size than the body dimension, which will generate much pressure on the body, leading to discomfort. As the pressure distribution may affect the pressure comfort and support performance of the sports bra, this study aimed to explore novel information in optimizing the pressure comfort and support performance by applying elasticity distribution. 4 sports bras with different elasticity distribution on the under-band were developed to compare with the one without elasticity distribution, and 12 healthy women were involved as subjects. The pressure distribution and pressure comfort sensations both in static and dynamic conditions, and the reduction of breast displacement (RBD) of 5 sports bras were measured and analysed by ANOVA analysis. The results indicated that the pressure distribution, the pressure comfort and RBD were effectively changed by elasticity distribution. Bra D with a high Young's modulus on the side area of the under-band was ideal and typical both in pressure comfort and RBD.

Keywords: *seamless knitted, sports bra, under-band, elasticity distribution, pressure comfort, breast support*

Distribuția elasticității benzii de susținere pe baza confortului și performanței de susținere pentru sutiene sport fără cusături

Sutienul sport tricotat fără cusături devine popular pentru performanța sa ridicată în tactilitate și confort la presiune, însă, cu toate acestea, se confruntă și cu problema suportului insuficient. Pentru a îmbunătăți performanța de susținere, acesta este întotdeauna tricotat cu material foarte elastic, într-o dimensiune mai redusă decât dimensiunea corpului, ceea ce va genera presiune ridicată asupra corpului, ducând la disconfort. Deoarece distribuția presiunii poate afecta confortul la presiune și performanța de susținere a sutienului sport, acest studiu și-a propus să exploreze informații noi în optimizarea confortului la presiune și a performanței de susținere prin aplicarea distribuției elasticității. Au fost dezvoltate 4 sutiene sport cu distribuție diferită a elasticității benzii de susținere pentru a fi comparate cu cele fără distribuție a elasticității, iar 12 persoane de sex feminin au fost implicate ca subiecți. Distribuția presiunii și senzațiile de confort la presiune atât în condiții statice, cât și dinamice, precum și reducerea deplasării sânilor (RBD) a celor 5 sutiene sport au fost măsurate și evaluate prin analiza ANOVA. Rezultatele au indicat că distribuția presiunii, confortul la presiune și RBD au fost modificate efectiv de distribuția elasticității. Sutienul D cu un modul Young ridicat pe zona laterală a benzii de susținere a fost ideal, atât în ceea ce privește confortul la presiune, cât și RBD.

Cuvinte-cheie: *tricotat fără cusături, sutien sport, bandă de susținere, distribuția elasticității, confort la presiune, susținerea sânilor*

INTRODUCTION

Due to the limited anatomical support, women's breasts will move relative to the chest wall when they participate in physical activities [1]. Therefore, sports bra, which was proven to be effective at reducing breast movement and exercise-related breast pain, has been advocated for exercising females [1]. Because of its high performance in tactility and pressure comfort, a seamless knitted sports bra is becoming popular. However, it also encounters some problems such as sizing, compression of the breasts, and especially insufficient support [2]. As a primary supporting part for breasts, the under-band of a seamless sports bra is often made with a strong elastic material in a reduced size than body dimension rather than cutting and combination of different fabrics in the under-band of a traditional bra. When it extends to adapt to body dimension during wearing, the fabric's tensile behaviour stores strain energy in the fabric, leading to the application of pressure on the skin [3]. If too loose, it will slide up and down the torso, and decrease the breast support performance during exercise [4]. If too tight, it will cause serious skin traces, result in uncomfortable feeling, or even heart, lung and bowel function injury for the wearer [5]. As a result, there is a contradiction between pressure comfort and support function for the under-band of a seamless sports bra. Most studies, however, only focused on pressure comfort or support function of the under-band [4, 6, 7], and there was limited research on how to optimize these two factors.

According to previous research, pressure comfort is not only affected by the value of pressure but also by the distribution of pressure. Due to the differences between pressure comfort thresholds (PCT), i.e., a feeling boundary between comfort and discomfort, between different body parts [8], the change in pressure distribution may cause a change in pressure comfort. It has been reported in some research about other garments that appropriate pressure distribution would improve subjective pressure comfort responses. For example, compression shaping pants with graduated pressure distribution could promote blood microcirculation of lower limbs and enhance wearing comfort [9]. However, the pressure distribution of the under-band has yet to be studied.

Elasticity distribution, i.e., applying fabrics with different Young's modulus in different areas, is a commonly used way to change pressure distribution. The pressure exerted on the body depends on the fabric tension and radius of the body curvature [3, 10]. As the radius of body curvature is a constant for a certain person, the pressure distribution could be changed by the fabric tension. With the same elongation, changes in Young's modulus will generate different levels of fabric tension and contact pressure to the body [11]. For seamless knitted fabric, elasticity distribution can be achieved by knitting with different structures, loop length or percentages of firm and soft yarns in different regions [2, 9, 12]. 4D garments fabricated by careful control of the percentages of firm and soft yarns could change the pressure distribution, and reduce uncomfortable pressure and unwanted sliding caused by body motion [12]. However, the effect of elasticity distribution of under-band on the pressure distribution, pressure comfort and the support performance of seamless sports bras has yet to be investigated.

This study aimed to explore the effect of elasticity distribution of under-band on the pressure distribution, pressure comfort and the support performance of seamless knitted sports bra, and search for appropriate elasticity distribution of the under-band which could improve the support performance without decreasing the pressure comfort of the seamless sports bra. Therefore, 5 seamless knitted sports bras with under-bands of different elasticity distribution were designed. The objective pressure, psychological pressure comfort sensations and the reduction of breast displacement (RBD) of these 5 bras were measured and compared. RBD is defined as the displacement percentage change (breast displacement without a bra minus breast displacement with a bra, divided by breast displacement without a bra), and is considered to be a unique evaluation standard of the supporting performance for sports bras [7]. It is hoped that the result could provide novel information in optimizing both the pressure comfort and breast support performance of sports bras to benefit exercising women.

METHODOLOGY

Participants

Following institutional ethical approval, 12 healthy, pre-menopausal and recreationally active women, who undertook 30 min of exercise more than twice a week were recruited for the experiment. And to minimize the potential between-participant effect in pressure comfort and breast displacement, all participants were chosen to be professionally fit to wear a 75B bra size [13]. The 3D body scanner ($(TC)^2$, US) was used to measure the subjects, and the mean and standard deviation (SD) of their anthropometric measurements were shown in table 1. The procedures of the experiment were carefully explained to all subjects before they signed the informed consent to participate. All participants had not experienced surgical procedures to the breasts or gone through pregnancy or breastfeeding and were not in their menstrual cycle. Participants were wearing the same type of sports pants and sports shoes and randomly wore one of these five bras (bras only on their upper body).

Table 1

ANTHROPOMETRIC MEASUREMENTS OF THE SUBJECTS

Anthropometric measurements	Mean	Std. D
Age	21.35	0.33
Weight (kg)	49.43	0.25
Height (cm)	159.76	0.93
BMI	19.37	0.31
Bust girth (cm)	87.17	1.12
Under-bust girth (cm)	75.42	0.77
Bust height (cm)	114.15	0.20
Under-bust height (cm)	108.13	0.27
Bust point width (cm)	20.07	0.12
Length from the front neck point to bust point (cm)	20.17	0.11
Vertical arc length from bust point to under-bust (cm)	7.59	0.04
Width of the breast (cm)	15.19	0.25
Height of the breast (cm)	6.03	0.14
Arc length of the outer side of the breast (cm)	10.30	0.18
Arc length of the inner side of the breast (cm)	8.20	0.14

Experiment samples

The experiment samples are 5 seamless knitted compression sports bras, with fibre contents of 53% Polyester, 33% Polyamide, and 14% Spandex for all parts. They were knitted by a seamless knitting machine (Santoni SM8-Top2, Italian) with 14" 28G 1248 Ndl, in the air-conditioned university workshop with the standard atmospheric condition (temperature: 23±1 °C; relative humidity: 65±3%). The sports bras were knitted with two yarns, polyester filament (100D) and nylon /spandex core-spun yarn (20/30 D).

The unit yarn feeding tension was set at 0.050 cN/dtex. Except for the only difference in the knitting structures, the yarns type, linear density, length, width, style and elongation of the under-band were kept the same, and other parts of the sports bras (such as straps, cups, back panels, etc.) were identical to each other, with the same size of 75 B according to the participants' anthropometric measurements (as shown in table 1).

4 points on the under-band were selected as the basis for elastic distribution: the centre front point, the point directly below the nipple, the intersection point of the under-band and side seam, the intersection point of the under-bust line and scapular line (points 1, 2, 3, and 4 in figure 1). These 4 points were selected based on the pressure measuring points proposed by Rong Zheng and the differences in the radius of body curvature which may affect the pressure distribution [2].

The under-band of these 5 sports bras were the same in length (60 cm) and width (2.5 cm).

2 popular knitting structures for under-band (Rib stitch 1×1 for structure I, and Rib stitch 2×2 for structure II) with different Young's modulus was used for elasticity distribution. The under-band of Bra A was knitted with structure I, the under-band of the other 4 sports bras was knitted with structure II 5 cm long in the area centred on these 4 points respectively, and structure I in the other areas (figure 2). Since the friction coefficients of these two structures were different (table 2), which might affect the mechanical properties of the under-band, a layer of fabric with the same width and length and low Young' modulus was sewed to the inner surface of the under-band to minimize the difference in friction coefficients for experiment purpose. And a strap with the inner fabric sewed to structure I and structure II were used for the tensile test, respectively. As the under-band mainly stretched in the course direction, and the radius of the curvature of the body in the wale direction is large, only Young's modulus in the course direction was measured.

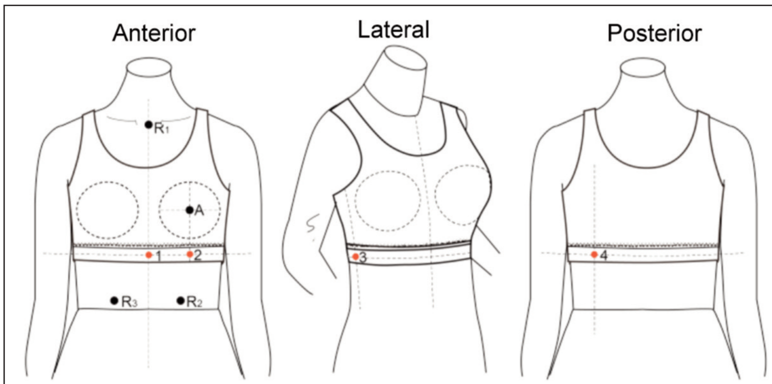
The tensile test was carried out with a tensile tester (Instron, USA), the density was tested with an electronic balance (XingYun, China), and the thickness was tested with a fabric thickness tester (FangYuan, China). The friction coefficient of the fabric was measured on a device modified after the tensile tester, based on the research of Lo et al. [14], the results were shown in table 2.

Experiment protocol

A parallel, randomized blinded design wear trial was carried out in a room with a temperature of 20±3°C and a relative humidity of 65±5%. The experiment protocols comprised 3 parts:

Part 1: *Objective pressure test*

The objective pressure test (both in static and dynamic conditions) method developed by Coltman et al. [15] was adopted and modified. A 5-minute duration was chosen to minimize participants' burden, although women usually exercise in sports bras for a much longer time. The pressure was measured by a custom-designed calibrated pressure sensor



Measuring point		Location
Pressure	1	The center front point
	2	The point directly below the nipple
	3	Intersection point of under-band and side seam
	4	Intersection point of under-band and scapular line
Breast movement	A	The nipple point
	R_1	Suprasternal notch
	R_2	left anteroinferior aspect of the 10th ribs
	R_3	right anteroinferior aspect of the 10th ribs

Fig. 1. Position of pressure sensors and reflective markers

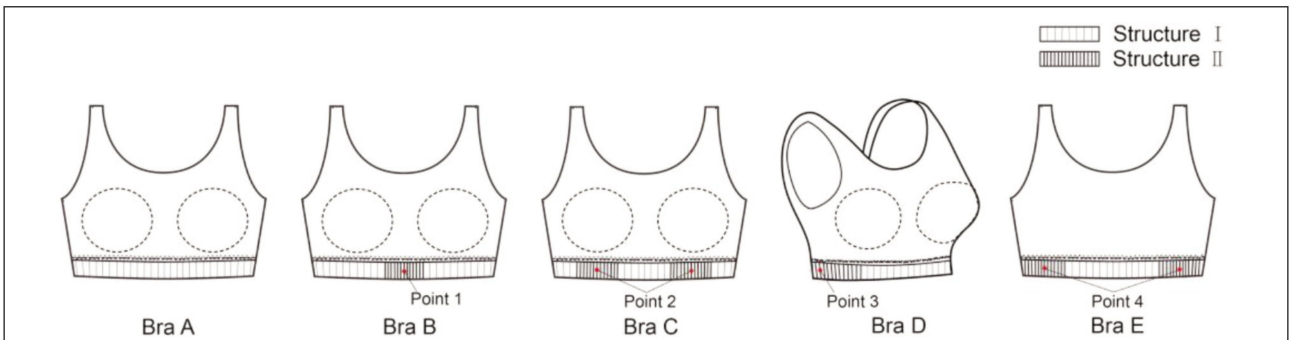
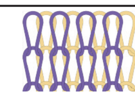
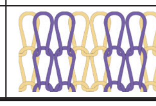


Fig. 2. Experimental samples

Table 2

DETAILS OF TWO KNITTING STRUCURES USED IN THE UNDER-BAND							
Knitting structure	**Fabric content**	**Knitting stitch**	**Thickness (mm)**	**Density (g/m^2)**	**Young's modulus (mPa)**	**Friction coefficient**	**Schematic structure**
I	53% polyester, 33% polyamide, and 14% spandex	Rib stitch 1×1	0.83	369.11	1.57	0.56	
II	53% polyester, 33% polyamide, and 14% spandex	Rib stitch 2×2	1.23	429.21	2.01	0.68	

(Novel, Germany). Participants ran in each sports bra condition for 5 minutes, and the static pressure was collected when participants sat and stood motionlessly in a controlled posture before running for 10 seconds respectively in both postures. The dynamic peak pressure was measured when participants were running on the treadmill at the speed of 7.5 km/h for 6 consecutive 10 seconds (the third minute). The test was repeated 3 times, and the average static pressure was taken as the average of the two 10-second periods in standing and sitting posture three times, while the dynamic peak pressure was taken as the average of the peak pressure in six 10-second periods three times.

Part 2: *Subjective pressure comfort test*

The Under-band pressure comfort was measured by questioning the wearers about their subjective compressive feelings to these 4 measuring points and the whole under-band in static (standing and sitting) and dynamic (running) conditions, using a compressive feeling scale (rated 1 to 5), whereby 1, 2, 3, 4, 5 represented compressive feelings from extremely weak (most comfortable) to extremely strong (least comfortable) respectively. The compressive feelings in static and dynamic conditions were tested right after the pressure in two conditions has been collected, and the test was also repeated 3 times.

Part 3: *Breast movement test*

The movement of the breast when wearing 5 bras and when naked was captured by the motion capture system (Qualisys, Sweden) during running. 1 retro-reflective marker was positioned on the nipple (or on the bra cup over the nipple), another 3 were positioned on the suprasternal notch, the left and right anteroinferior aspect of the 10^{th} ribs as the trunk reference as shown in figure 1 (points A and R_1, R_2, R_3), to record the movement of breasts with or without bras in three directions (x as anterior-posterior, y as medial-lateral, and z as vertical direction) [16].

Similarly, the displacement was measured when participants were running on the treadmill for 6 consecutive 10 seconds (the third minute of running). The displacement of the breast (maximum displacement minus minimum displacement in a gait cycle) when naked and when wearing 5 sports bras and the RBD (breast displacement without bra minus breast displacement with a bra, divided by breast displacement without bra) of 5 sports bras were calculated.

Statistical analysis

The data were statistically analysed using SPSS version 25.0. The pressure of 4 points, the RBD and the subjective compressive feelings were analysed by repeated-measures analysis of variance (ANOVA). Upon detection of a significant difference in the ANOVA test, a post hoc test was performed to examine the pairwise comparison. The significance level was set at $P < 0.05$, and $P < 0.001$ (a very significant difference) was also marked. Effect sizes were calculated using partial eta squared ($\eta^2_{partial}$), and it was defined as a small effect when $\eta^2_{partial} > 0.01$, a medium effect when $\eta^2_{partial} > 0.06$, and a large effect when $\eta^2_{partial} > 0.14$, according to Cohen (1988).

RESULTS AND DISCUSSION

Pressure distribution

Repeated-measures analysis of ANOVA showed that there were significant pressure differences in sports bras ($P < 0.001$, $F = 52.875$, $\eta^2_{partial} = 0.794$ for static condition, and $P < 0.001$, $F = 69.634$, $\eta^2_{partial} = 0.835$ for dynamic condition), measuring point ($P < 0.001$, $F = 2631.069$, $\eta^2_{partial} = 0.980$ for static condition, and $P < 0.001$, $F = 2914.062$, $\eta^2_{partial} = 0.981$ for dynamic condition), and sports bras by measuring point interaction effect ($P < 0.001$, $F = 44.881$, $\eta^2_{partial} = 0.765$ for static condition, and $P < 0.001$, $F = 60.403$, $\eta^2_{partial} = 0.815$ for dynamic condition). The results revealed that the elasticity distribution significantly affected the pressure distribution of the under-bands of these 5 seamless sports bras both in static and dynamic conditions, and the effect varied with bras and measuring points. The dynamic peak pressure showed a much similar distribution to the static pressure except a little higher value at all 4 points (up to 0.20 kPa at point 3 of Bra D), as shown in figure 3. The pressure differences between these two conditions (static and dynamic) were much smaller than other parts of sports bras, such as a strap, which was reported to be 5.1 kPa [15]. This might be attributed to the lower deformation in the under-band than other parts during exercise.

When Compared to Bra A (without elasticity distribution), the pressure of the other 4 sports bras increased not only at the centre point of section II (the section knitted with structure II) but also at other

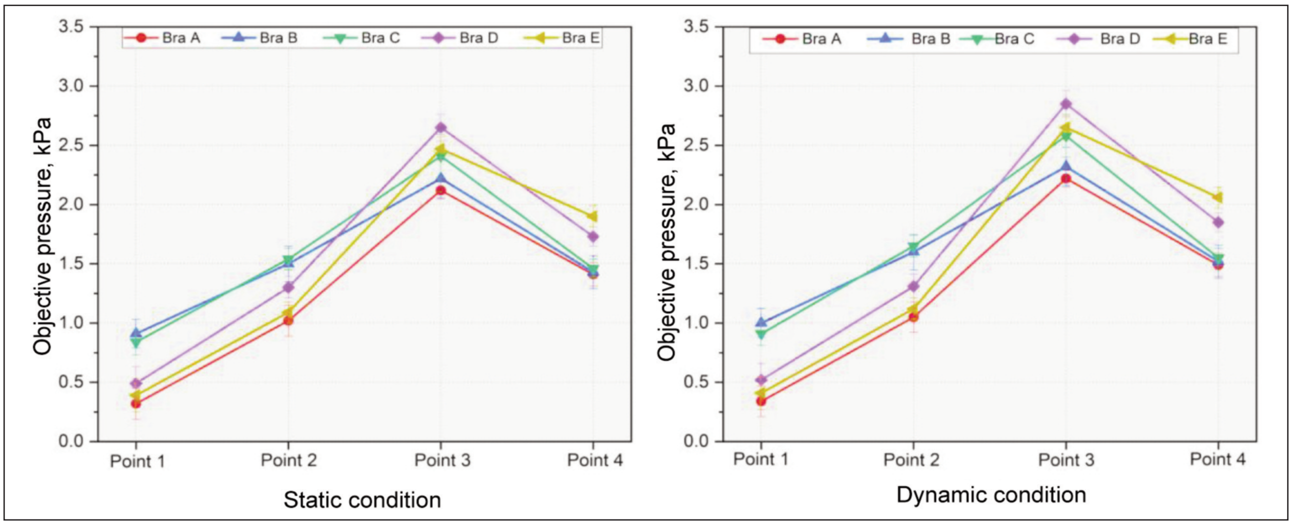


Fig. 3. The pressure distribution of 5 seamless sports bras

Table 3

THE PRESSURE INCREMENTS OF 4 SPORTS BRAS COMPARED TO BRA A

Sports Bra		**Static pressure increments (kPa)**				**Dynamic peak pressure increments (kPa)**			
		Measuring point				**Measuring point**			
		1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
B	Mean	**0.59**	0.48	0.10	0.02	**0.66**	0.55	0.10	0.03
	Std. D	0.07	0.11	0.13	0.09	0.09	0.10	0.11	0.15
C	Mean	0.52	**0.52**	0.29	0.05	0.57	**0.60**	0.36	0.06
	Std. D	0.06	0.07	0.15	0.03	0.05	0.09	0.13	0.08
D	Mean	0.17	0.28	**0.53**	0.32	0.08	0.26	**0.63**	0.36
	Std. D	0.12	0.04	0.06	0.03	0.09	0.05	0.07	0.06
E	Mean	0.07	0.07	0.35	**0.49**	0.07	0.07	0.43	**0.57**
	Std. D	0.09	0.13	0.08	0.04	0.12	0.10	0.05	0.06

Note: The data underlined: the pressure increments of the centre point of section II (the section knitted with structure II) on the under-band for 4 seamless sports bras with elasticity distribution, compared to Bra A (without elasticity distribution).

measuring points in both conditions. And the pressure increment seemed to be related to the distance from the measuring point to the centre point of section II. The centre point often showed a larger pressure increment, while the point far away from it showed a smaller pressure increment, as shown in table 3. For example, the largest pressure increments of Bra B occurred at point 1, followed by points 2, 3 and 4, in both conditions. This might have been because a high-modulus section would make the section nearby stretch more, resulting in larger elongation and thus higher pressure, which was also observed in previous studies [12].

Pressure comfort

The elasticity distribution also significantly affected the compressive feelings of the under-band both in static and dynamic conditions. The result of repeated-measures analysis of ANOVA showed significant differences in sports bra ($P < 0.001$, $F = 51.650$, $\eta^2_{partial} = 0.790$ for static condition, and $P < 0.001$, $F = 72.877$, $\eta^2_{partial} = 0.841$ for dynamic condition), measuring point ($P < 0.001$, $F = 2307.771$, $\eta^2_{partial} = 0.977$ for static condition, and $P < 0.001$, $F = 2768.904$, $\eta^2_{partial} = 0.982$ for dynamic condition), and sports bra by measuring point interaction effect ($P < 0.001$, $F = 38.484$, $\eta^2_{partial} = 0.737$ for static condition, and $P < 0.001$, $F = 58.350$, $\eta^2_{partial} = 0.809$ for dynamic condition). The dynamic compressive feelings showed a little higher score than static compressive feelings at all 4 points, however, the differences between these 5 sports bras were similar to the static condition, as shown in figure 4.

Bra A, D, and E performed satisfactorily in comfort performance, which showed low compressive feelings at all 4 points (ranging from 1.65~2.23 for static condition, and 1.85~2.43 for dynamic condition). Bra B and C exhibited low compressive feelings at points 3 and 4 (ranging from 1.87~1.98 for static condition, and 2.07~2.25 for dynamic condition), but high compressive feelings at points 1 and 2 (up to 4.01 for static condition and 4.21 for dynamic condition at point 2

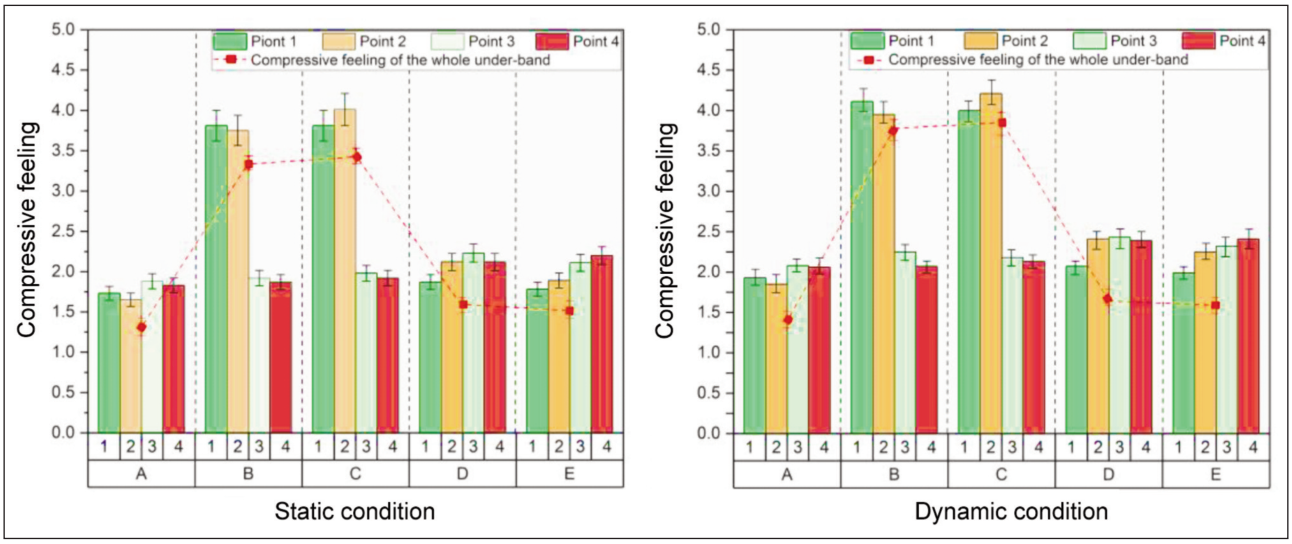


Fig. 4. The compressive feelings of 5 seamless sports bras

of Bra C), significantly higher than that of Bra A, D, and E (P<0.001).

Compared with the pressure distribution, although Bra B and C showed much lower pressure at points 1 and 2 than at point 3 (figure 3), the compressive feelings of points 1 and 2 were much higher than at point 3. The results indicated a much lower PCT at points 1 and 2 which was also observed in previous research [17]. Therefore, Bra B and C which mainly increased pressure at points 1 and 2, tended to make the pressure of these two points higher than PCT, resulting in pressure discomfort.

The compressive feelings of the whole under-band of these 5 sports bras showed consistent results, and there was also a significant difference between sports bras ($F = 42.167$, $P < 0.001$, $\eta^2_{partial} = 0.754$ for static condition, and $F = 38.218$, $P < 0.001$, $\eta^2_{partial} = 0.735$ for dynamic condition). Bra B and C which exerted significantly higher compressive feelings at points 1 and 2, also showed significantly higher compressive feelings of the whole under-band, than Bra A, D, and E ($P < 0.001$).

Reduction of breast displacement (RBD)

Significant differences in bra ($F = 268.924$, $P < 0.001$, $\eta^2_{partial} = 0.951$), direction ($F = 2516.400$, $P < 0.001$, $\eta^2_{partial} = 0.979$), and bra by direction interaction effect ($F = 10.287$, $P < 0.001$, $\eta^2_{partial} = 0.428$) in RBD was detected. It indicated that there were significant differences in RBD between these 5 sports bras and the differences varied with directions. Bra B, C and D performed significantly better than Bra A and E in all three directions ($P < 0.001$) while there was no significant difference between Bra A and E.

Moreover, Bra B, C and D showed different RBD performances in different directions, of which Bra C performed best in all three directions. Bra C showed a significantly higher RBD than Bra D in direction X ($P < 0.05$) and Y ($P < 0.001$), and a significantly higher RBD than Bra B in direction Z ($P < 0.05$). Bra B performed significantly better than Bra D in the direction Y ($P < 0.001$).

The results indicated that the elasticity distribution of Bra B, C and D could significantly improve RBD in all 3 directions. During running, breast displacement mainly occurs in the vertical direction. In the process of the breast's upward (or downward) movement, the points surrounding the breast (such as points 1, 2 and 3) may receive a large pulling force (or impact), making it no longer in firm contact with the sternum, or result in the sliding of under-bands which were often reported in previous researches [4, 7, 18]. The pressure increments in these 3 points increased the friction between the under-band and the skin, attached the bra firmly to the trunk and reduced the occurrence of sliding, which subsequently led to a better performance in RBD.

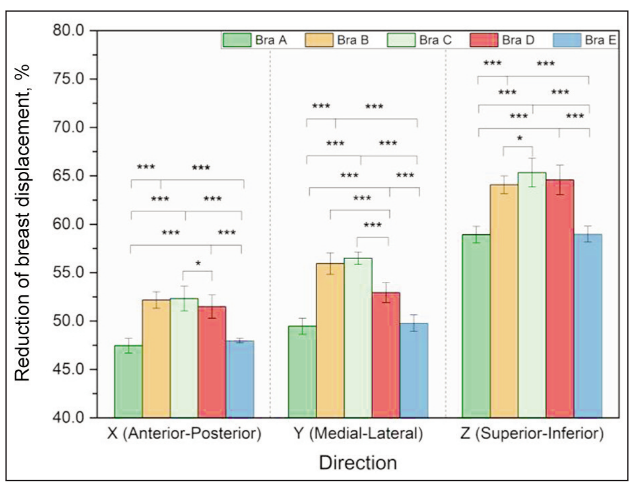


Fig. 5. RBD of 5 seamless sports bras in 3 directions

CONCLUSION

This study provided novel information in optimizing the pressure comfort and support performance for seamless knitted sports bras, by applying elasticity distribution in the under-band. The results showed that elasticity distribution significantly affected the pressure distribution, compressive feelings and RBD of the seamless sports bras, in both static and dynamic conditions ($P < 0.001$).

No matter where the fabric structure with high Young's modulus was used in the under-band, the pressure increased at each point. And the pressure increment appeared to be related to the distance from the high-modulus section to the measuring point, for both conditions. Compared to Bra A, the elasticity distribution of Bra B, C and D mainly increased the pressure at points around the breasts (points 1, 2 and 3), significantly improving the support performance ($P < 0.001$). However, Bra B and C also showed significantly higher compressive feelings for points 1 and 2, and the whole under-band ($P < 0.001$). Bra E mainly increased the pressure at points 4 and 3 and showed no significant difference in compressive feelings or support performance with Bra A. Comprehensively, Bra D was ideal and typical, which significantly improved the support performance ($P < 0.001$) without increasing compressive feelings. Therefore, it is suggested that applying a high-modulus structure (e.g., Rib stitch 2×2) around the intersection point of the under-band and side seam (Point 3), and a low-modulus structure (e.g., Rib stitch 1×1) in another area, to improve the breast support performance without decreasing pressure comfort. Moreover, the friction coefficient should also be taken into consideration, as the decrease of friction coefficient may lead to lower friction of the points around the breasts, resulting in the decrease of RBD. To minimize the influence of friction coefficient ($\mu_{II} > \mu_{I}$), we sewed a layer of the same fabric to the inner surface of the under-band for experiment purposes only. Without this layer, the friction of Bra B, C and D at the points around the breast would be even higher, which might result in an even better performance in RBD. However, some structures may decrease the friction coefficient, which may contribute to the decrease of RBD, future studies should also pay attention to the effect of elasticity distribution on friction.

As this study is a new attempt to optimize the pressure comfort and RBD of the seamless sports bra by applying elasticity distribution in the under-band, only 2 fabric structures and 4 measuring points were chosen. Future work may involve more different measuring points, yarn type, linear density, knitting structures, elongations, sizes and so on, as these factors may also affect the pressure comfort and breast support performance of seamless sports bras. Furthermore, a large-scale experiment with stratified depth randomization will be needed for future research to benefit more exercising women of different ages, body mass, and breast size.

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