









## Original research

### How the characteristics of sports bras affect their performance.

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## **How the characteristics of sports bras affect their performance.**

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### **Abstract**

Breast movement reduction (%) measures breast support and sports bra performance, however limited evidence exists on the sports bra characteristics which affect it. This study investigated breast movement reduction achieved by 98 sports bras, the categorization of support levels, and the characteristics that contribute. Each bra was tested on ~12 females (total n=77). Relative breast position was recorded during sports bra and bare-breasted running, and breast movement reduction calculated; low, medium, high breast support tertiles were identified and compared to brand-classified support levels. Ten bra characteristics were identified, and regressions determined which characteristics contributed to performance. Breast movement reduction ranged from 36% to 74%; 69% of bras marketed as high support were in the high support tertile (>63%). Encapsulation style, padded cups, nylon, adjustable underband and high neck drop accounted for 37.1% of breast movement reduction variance. Findings facilitate high performance sports bra development and inform consumer choice.

**Keywords:** Bra, breast health; breast support; exercise; running.

### **Practitioner Summary**

Little is known about the biomechanical breast support which sports bras actually provide. This original research facilitates high performance sports bra development, and helps inform consumer

choice, by identifying the breast movement reduction of a large sample of sports bras, and the characteristics which impact sports bra performance.

## 1. Introduction

During activities such as walking, running and stepping, breast movement reduction (Zhou et al. 2013, 2009) compares three-dimensional range of motion (ROM) of the breast in a bra to that bare-breasted (Zhou et al. 2013). Within the sports bra market, breast movement reduction is often used as an outcome measure to determine the breast support provided by garments and consequently may be used as a surrogate measure of sports bra performance (Zhou et al. 2013) (Shock Absorber<sup>®</sup> (Josephson, 2015), Triumph<sup>®</sup> (Triumph, 2019)). Represented as a percentage, breast movement reduction has been identified to range from 50% (Triumph, 2019) to 78% (Shock Absorber, 2020) in the sports bra market, with similar values also previously reported within breast biomechanics literature (59%, Scurr et al. (2011), 53% and 64%, Boschma et al. (1994)). Additionally, compared to other performance outcome measures utilised within breast biomechanics research such as strap pressure (Bowles and Steele, 2013), bra comfort (Lawson and Lorentzen, 1990), thermal comfort (Ayres et al. 2013), skin temperature (Ayres et al. 2013), and muscular activity (Milligan et al. 2014), it has been suggested that reporting the percentage of breast movement reduction achieved for a sports bra helps the consumer understand the support that bra may provide (Bowles et al. 2008; Krenzer et al. 2005).

Within the sports bra market, breast movement reduction may be conveyed to consumers through, or in association with, brand-classified breast support levels which are often detailed on the garment or accompanying marketing material. Shock Absorber<sup>®</sup> identify their Ultimate Run Bra<sup>®</sup> as providing 78% breast movement reduction and is brand-classified as an Extreme Impact sports bra (Shock Absorber, 2020), whilst Triumph<sup>®</sup> identify their range of Extreme Bounce Control sports bras as providing above 68% breast movement reduction (Triumph, 2019). However, to the authors knowledge, there are no breast movement reduction (%) thresholds published which determine what positions a sports bra within a specific support level. The most common brand-classified breast

support levels on the sports bra market are low/light, medium and high/extreme support or impact (Adidas, 2020; Gymshark, 2020; Knix, 2020; Nike, 2020). Segmenting breast movement reduction values into tertiles, which represent low, medium and high breast support would provide the bra industry with initial thresholds based on the range of breast movement reduction achieved by current products, and against which their products could be assessed. However, findings based on this method represent a snapshot related to the range of bras tested within the sample. Without an evidence-based threshold which defines the necessary amount of breast movement reduction that a sports bra should achieve, the division of the performance a large sample of sports bras into tertiles represents a starting point for the bra industry and one which future studies can contribute.

To further inform the development of supportive sports bras it is also important to identify sports bra characteristics which contribute to reduced breast movement. During running Zhou, Yu and Ng, (2013) identified that better performing sports bras reduced breast movement and contained characteristics such as compression, high neck drop, cross back shoulder straps, no padding and no underwire. Similarly, Scurr et al. (2011) also utilised breast movement reduction to assess sports bra performance during running, however Scurr et al. (2011) identified an encapsulation style as better performing than a compression style for larger-breasted females (D cup). Zhou et al. (2009) also utilised breast movement reduction to report that better performing bras, during walking, stepping and running, contained increased polyamide (commonly identified as nylon (Deopura et al. 2008)) content. While previous research indicates that breast movement reduction is sensitive to variations in sports bra characteristics, studies investigating optimum sports bra characteristics have typically compared a limited number of sports bras (a maximum of eight bras (Ayres et al. 2013; Lawson and Lorentzen, 1990; Lorentzen and Lawson, 1987; McGhee and Steele, 2010; White et al. 2011, 2009; Zhou et al. 2013, 2009) or have investigated a limited number of sport bra characteristics (a maximum of five characteristics (Jang et al. 2013; Liu et al. 2019), with only Zhou, Yu and Ng, (2013) investigating greater than ten characteristics, however these were only tested on four participants.

Research on optimum sports bra characteristics has used one of two approaches (Bowles and Steele, 2013; Coltman et al. 2015; Scurr et al. 2011; Zhou et al. 2013, 2009); (1) utilising an adjustable sports bra upon which individual characteristics (i.e. shoulder strap configuration) can be altered (Bowles and Steele, 2013; Coltman et al. 2015), (2) utilising a large sample of sports bras with different characteristics (White et al. 2011; Zhou et al. 2013, 2009), neither approach is without limitations. With the first approach, an adjustable sports bra enables the altered bra characteristic to be isolated and the effect on performance measured. However, obtaining an adjustable sports bra with individual characteristics that can be altered may be difficult, costly, and time-consuming. Additionally, altering one characteristic is likely to alter others, e.g. a tighter underband may alter the cup and shoulder strap positioning. With the second approach, assessing the performance of a large sample of sports bras which incorporate bras with different characteristics helps our understanding of the performance of the sports bra market (Davies, 2017). However, with this approach there is no control over the alteration of individual characteristics and where multiple characteristics are altered, it may be difficult to determine the effectiveness of individual characteristics. This approach necessitates a large sample of sports bras to determine the importance of individual characteristics.

Regardless of the approach, it is also important to consider which characteristics are investigated. For example, characteristics such as bra style (Page and Steele, 1999; White et al. 2009; Yu and Zhou, 2016; Zhou et al. 2013), underwire presence (Page and Steele, 1999; Zhou et al. 2013), shoulder strap adjustability (Zhou et al. 2013), shoulder strap configuration (Bowles and Steele, 2013; Coltman et al. 2015; Page and Steele, 1999; Yu and Zhou, 2016; Zhou et al. 2013), principal fibre content (Page and Steele, 1999; Yu and Zhou, 2016; Zhou et al. 2013), underband adjustability (Zhou et al. 2013), cup padding presence (Lu et al. 2016; Page and Steele, 1999; Yu and Zhou, 2016; Zhou et al. 2013), underband closure location (Zhou et al. 2013) and neck drop (Yu and Zhou, 2016) have all been reported to affect sports bra performance (Bowles and Steele, 2013; Coltman et al. 2015; Lu et al. 2016; Page and Steele, 1999; White et al. 2009; Yu and Zhou, 2016; Zhou et al. 2013); where sports bra performance was measured using many outcome measures such as breast movement reduction, bra strap pressure, breast displacement etc. It is suggested that these characteristics have the potential to

affect the mechanical properties of the sports bra, and therefore their inclusion in previous research studies is understandable. Likewise, underband closure type (e.g. zip, hook and eye), whilst not previously investigated, may also be important in terms of assessing sports bra performance, as it allows for adjusting underband tightness and therefore potentially altering the mechanical properties of the sports bra.

Given the above, this study firstly aimed to measure breast movement reduction (%) during running to investigate the performance of a large sample of sports bras. Secondly, we wished to use this large sample to present the first estimate of breast movement reduction in tertiles representing low, medium and high breast support, and compare these outcomes to the sports bras brand-classified breast support level. Lastly, we investigated the affect of ten sport bra characteristics (bra style, underwire presence, shoulder strap adjustability, shoulder strap configuration, principal fibre content, underband adjustability, cup padding presence, underband closure type, underband closure location and neck drop) on sports bra performance during running, utilising breast movement reduction as a surrogate sports bra performance measure.

## **2. Methods**

### **2.1 Participants and sports bra sample**

Following institutional ethical approval, 77 females (n = 37, mode 34B, n = 40, mode 34D) gave written informed consent to participate (Table 1). Bra sizes 34B and 34D were selected as they represent both smaller (A to C cup) and larger ( $\geq$ D cup) breasted females (McGhee et al. 2013, White et al. 2015). Participants were recruited from February 2016 to June 2018. Participants were aged between 18 and 36 years, had not given birth or breast-fed within the last 12 months and had not undergone any surgical procedures to their breasts. Participants had their bra size assessed by a trained bra fitter using best-fit criteria (McGhee and Steele, 2010).

Ninety-eight sports bras were assessed (34B, n=27, 34D, n=71). Each sports bra was tested on an average of 12 participants (standard deviation (SD) of 1), with each sports bra further fitted to each

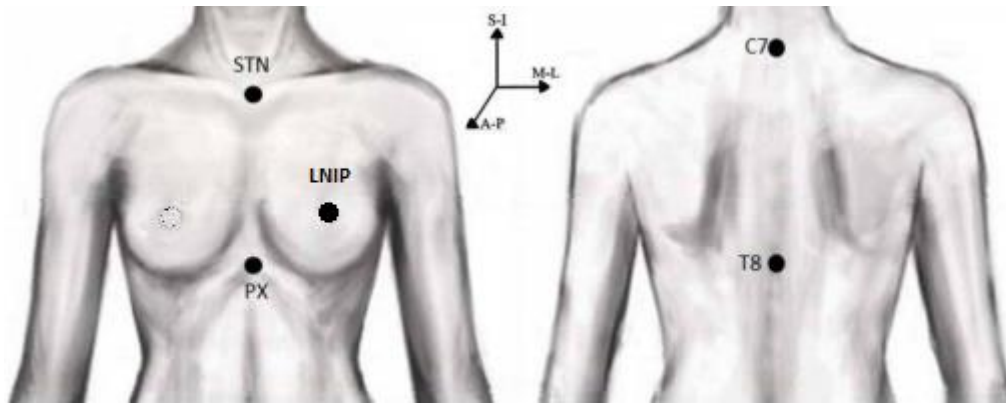
participant where possible (sports bras with an adaptable underband and/or adaptable shoulder straps). Participants were omitted from testing sports bras which did not fit correctly. Of the 77 participants included in the study, 50 undertook multiple testing sessions with different bras (averaging four testing sessions), while 27 only undertook one testing session. Repeat participants were treated as new participants as their characteristics, including their bra size and age may have changed within the testing period. This gave a total sample of 1,173 cases (34B, n = 321, 34D, n = 852). Each case comprised of a participant running in a sports bra.

**Table 1. Mean (and range) participant characteristics (n =77).**

Fitted bra size	Number of cases	Age [years]	Body mass [kg]	BMI	Underband [cm]	Bust circumference [cm]
<b>34B</b>	321	25 (18 to 32)	64 (50 to 82)	22.2 (18.8 to 27.6)	78 (69 to 87)	89 (84 to 97)
<b>34D</b>	852	25 (18 to 36)	65 (54 to 80)	23.2 (19.8 to 28.3)	76 (70 to 89)	92 (74 to 104)

## 2.2 Kinematic data

To measure breast movement reduction, breast and torso positional data were recorded at 240 Hz using an electromagnetic, 5-sensor model (Liberty Micro Sensor 1.8, Polhemus, USA; outer diameter, 1.8 mm; mass,  $\leq 1.0$  g). The 5-sensor model comprised of a sensor on the suprasternal notch (STN), xiphoid process (PX), 7th cervical vertebrae (C7), 8<sup>th</sup> thoracic vertebrae (T8) and left nipple (LNIP) (Mills et al. 2016). Torso sensors enabled breast movement to be quantified relative to the torso (Mills et al. 2016) (Figure 1). All electromagnetic sensors were securely attached to the participants breast and torso using hypoallergenic tape, which ensured that the sensors did not protrude from the participants breast and torso, and that there was limited sensor movement at the sensor attachment site.



**Figure 1. Sensors configuration (adapted from Mills et al. 2016). STN = suprasternal notch, PX = xiphoid process, C7 = 7<sup>th</sup> cervical vertebrae, T8 = 8<sup>th</sup> thoracic vertebrae and LNIP = left nipple, S-I = superior-inferior axis, M-L = medial-lateral axis, A-P = anterior-posterior axis.**  
**Figure 1 Alt Text.** The front and back of a female torso, with black circles superimposed representing sensor positions, along with an axis depicting the orientation of the sensors.

Before data collection, participants ran on a treadmill (h/p/cosmos mercury<sup>®</sup>, Nussdorf–Traunstein, Germany) with zero gradient for 10 s at 2.8 m·s<sup>-1</sup> (10.0 km·h<sup>-1</sup>) (Scurr et al. 2009), to ensure participants had adapted to the running speed. Participants then continued to run for a further 30 s during which sensor positional data were recorded. Participants performed this activity in an average of 4.7 (SD 2.7) sports bras per testing session (range from 1 to 12 sports bras) and bare-breasted.

All positional data from the electromagnetic sensors were exported to Visual 3D (v4.96.4, C-Motion) and filtered using a recursive 2nd-order low-pass Butterworth filter with a cut-off frequency of 13 Hz (Mills et al. 2015). A torso segment was created to provide a local coordinate system for the 5-sensor model (Mills et al. 2016). Briefly, the proximal end of the segment was the midpoint between the suprasternal notch and C7 sensors, and the distal end of the segment was the midpoint between the xiphoid process and T8 sensors. Gait cycles were identified using every other inferior minima of the suprasternal notch sensor (Norris et al. 2019) and the first ten gait cycles within the 30 s data collection period were utilised for analyses.

To quantify breast movement, nipple position was calculated relative to the local coordinate system of the torso in three directions: superior-inferior (S-I), anterior-posterior (A-P) and medial-lateral (M-L) (Norris et al. 2019). Nipple ROM was calculated within each gait cycle as the maximum displacement



minus the minimum displacement for each axis (cm) which was then averaged across the ten gait cycles to provide representative breast movement during running. Resultant nipple ROM was calculated as,

*Resultant nipple ROM (cm) =*

$$\sqrt{(ROM_{superior-inferior}^2) + (ROM_{anterior-posterior}^2) + (ROM_{medial-lateral}^2)}$$

(1)

Breast movement reduction (%) was calculated in each axis and hereafter as a resultant using;

$$Breast\ movement\ reduction\ (\%) = \left(1 - \left(\frac{Sports\ bra\ resultant\ nipple\ (ROM)(cm)}{Bare-breasted\ resultant\ nipple\ (ROM)(cm)}\right)\right) \times 100$$

(2)

### **2.3 Sports bra support levels**

To identify the biomechanical breast support provided by each sports bra, breast movement reduction (%) values were divided into low, medium and high support tertiles, using the 33<sup>rd</sup> and 66<sup>th</sup> percentiles of all breast movement reduction values as cut off points. The brand-classified breast support level (low, medium or high support) of each sports bra was identified via the sports bra tag, branding or packaging which accompanied the sports bra, or online. Sports bras which did not have a brand-classified support level, were not on the market, or were under development were classified as prototype/undefined support.

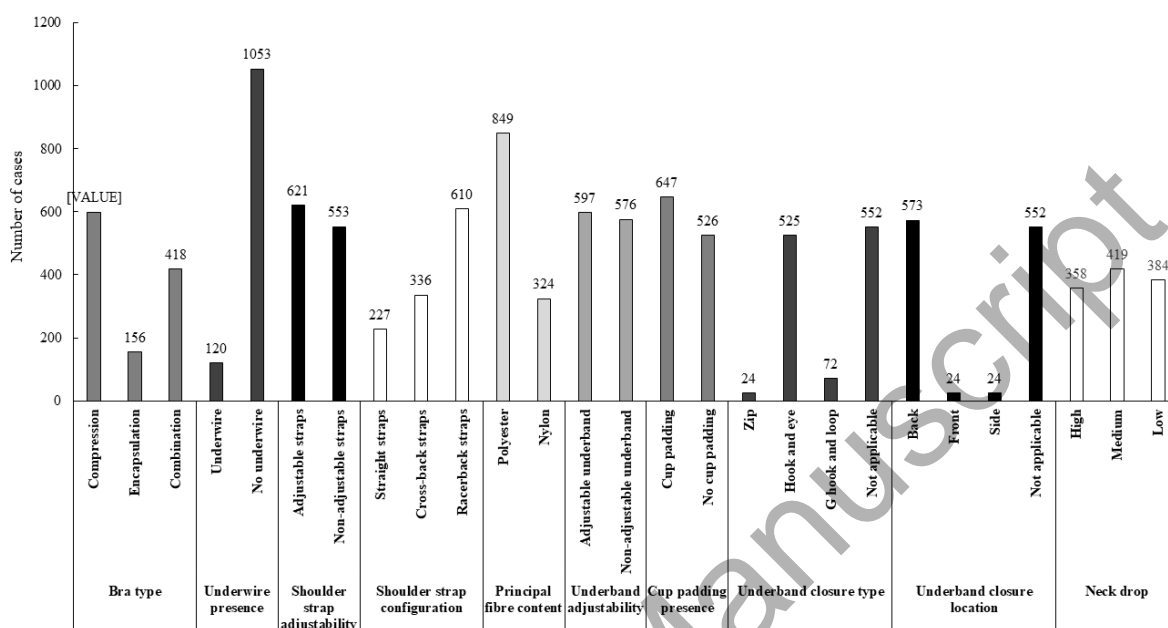
### **2.3 Sports bra characteristic assessment**

To categorise the ten sports bra characteristics, each sports bra was independently assessed by three experienced breast biomechanics researchers (Table 2). Any sports bra characteristic which was not agreed by all researchers, was discussed until a unanimous decision was reached.

Characteristic	Category/s	Definition/s
1. Bra style	a) Compression b) Encapsulation c) Combination	a) The compression sports bra is designed to restrict breast movement by flattening the breasts against the chest wall (Page and Steele, 1999). A compression sports bra generally has a higher neck drop, wider shoulder straps, and larger back panels compared to an encapsulation sports bra (Yu and Zhou, 2016). b) The encapsulation sports bra contains two moulded or structured cups and a centre gore which support two separated breasts (Page and Steele, 1999). The centre gore separates the two breasts, whilst the cups hold the breasts in place, so the breast shape is less distorted (Yu and Zhou, 2016). c) The combination sports bra encapsulates and compresses each breast against the chest wall. Combination bras use some cup definition to separate breasts, and a front panel on the anterior of the sports bra which causes some breast compression.
2. Underwire presence	a) Underwire b) No underwire	a) Any underwire present which circles the side and/or bottom of each cup. Could be either wire or moulded plastic. b) No underwire present.
3. Shoulder strap adjustability	a) Adjustable straps b) Non-adjustable straps	a) Any shoulder strap adjustability (e.g. slider, ladder) which allows straps to be shortened and/or lengthened. b) Shoulder straps which cannot be shortened and/or lengthened.
4. Shoulder strap configuration	a) Straight straps b) Cross back straps c) Racerback straps	a) Also known as a “U” back, where the shoulder straps do not meet prior to (or approximately at) the underband. b) Where the shoulder straps physically cross over or underneath each other but are not attached to one another. c) Where the shoulder straps are attached to one another between the shoulder blades (includes T back and Y back shoulder strap configurations).
5. Principal fibre content	a) Polyester b) Nylon	The highest percentage fibre content within the sports bra, as identified via the tag/label. Note: No bras within this study were identified to primarily be composed of bamboo, cotton, elastane etc. and therefore these were not included as categories.
6. Underband adjustability	a) Adjustable underband b) Non-adjustable underband	a) Any underband adjustability (e.g. hook and eye, Velcro) which allows the underband to be loosened or tightened. b) Underband which cannot be loosened or tightened.
7. Cup padding presence	a) Cup padding b) No cup padding	a) Any padding present in the cup including moulded or removable (if tested with padding inserted). Multiple layers of fabric were not classified as padding. b) No padding present in the cup.
8. Underband closure type	a) Zip b) Hook and eye c) G hook and loop d) Not applicable	a) A fastener which binds together fabric typically seen in clothing and bags. b) A hook which fastens onto an eyelet, commonly seen in the underband of everyday bras. c) A “G” shape hook which can be composed of metal or plastic and attaches to a loop of material for fastening. d) There is no closure type. Note: No bras within this study displayed any other closure types such as slider and Velcro, and therefore these were not included as categories.
9. Underband closure location	a) Back b) Front c) Side d) Not applicable	a) Located on the back of the sports bra. b) Located on the front of the sports bra. c) Located at either or both sides of the sports bra. d) There is no closure on the underband.
10. Neck drop*	a) High b) Medium c) Low	The vertical distance (cm) from the sternal notch to the top of the sports bra, measured on a standardised mannequin. a) < 9.9 cm from the sternal notch to the top of the sports bra. b) ≥ 9.9 cm and ≤ 11.6 cm from the sternal notch to the top of the sports bra. c) >11.6 cm from the sternal notch to the top of the sports bra.

**Table 2. Sports bra characteristics, characteristic category, and category definition.**

In general, each category had greater than 120 cases, except for zip, underband (closure type), front closure, and side closure, which were not well balanced and only accounted for 2.1% of total cases (24 cases each) (Figure 2).



**Figure 2.** The distribution of sports bra characteristics within the total number of cases (n=1,173). Note: one sports bra (12 cases) was unable to be assessed for neck drop.

**Figure 2 Alt Text.** A column chart displaying the number of cases within each sports bra characteristic. One sports bra (12 cases) is not included for neck drop.

## 2.4 Data analysis

Mean breast movement reduction (%) was calculated for each bra. Newly assigned tertiles (low, medium and high support) based on breast movement reduction were then compared to brand-classified support levels (low, medium, high and prototype/undefined). Following this, all category combinations within the sample of sports bras were identified, (i.e. the number of bras with a combination style, underwire present, adjustable shoulder straps, cross back, nylon, adjustable underband, cup padding, hook and eye closure and low neck drop, and so on), resulting in 58 category combinations, and descriptive statistics (mean and SD) for breast movement reduction (%) were

calculated for each category combination. The breast movement reduction achieved by the individual best and worst performing sports bras, along with their associated characteristic categories, were also identified.

To identify characteristics which may affect sports bra performance a multiple linear regression was used. Categorical characteristics were dummy coded (Cohen, 1991) (except for neck drop which was a continuous variable). For dummy coding, a characteristic with  $k$  categories e.g. (bra style,  $k = 3$ , compression, encapsulation and combination) requires a set of  $k-1$  dummy variables to capture all the distributional information from the original categories (Hardy, 1993). Therefore, characteristics with two categories (e.g. principal fibre content) were reduced to a single dichotomous variable, and characteristics with three categories (e.g. bra style, closure type) were reduced to two dichotomous variables. Stepwise multiple linear regression was then calculated to predict breast movement reduction (%) based on the sport bra characteristics of underwire presence, shoulder strap adjustability, shoulder strap configuration, principal fibre content, underband adjustability, cup padding presence, and neck drop, with confounding variables (BMI and bra style) adjusted for within the models. Underband closure type and underband closure location were omitted due to their strong association with underband adjustability. Bra style was included as a confounding variable as previous research identified that bra style has an effect on sports bra performance (Page and Steele, 1999; White et al. 2009; Yu and Zhou, 2016; Zhou et al. 2013). BMI was included as a confounding variable as BMI has been closely associated to breast size (Brown et al. 2012; Coltman et al. 2017), with larger breast sizes resulting in increased breast movement (Brown and Scurr, 2016) which may impact sports bra performance. When selecting the reference category, Hardy (1993) identified that while the selection of specific reference category variables is arbitrary, the variables should be well defined and contains a sufficient number of cases. Within the current study, as all sports bra characteristics included within the stepwise multiple linear regression were well defined and contained  $\geq 120$  cases, the reference category was randomly selected. The reference category was therefore identified as a compression bra, with underwire; adjustable racerback shoulder straps, with a principal fibre content of polyester, an adjustable underband, and no cup padding. Parameters generated within the multiple

regression model denoted any difference or deviation from the reference category for categorical characteristics and a one-unit change in continuous variables (BMI and neck drop) (Cohen, 1991). Prior to running the multiple regression model, data were assessed for linearity, independence of errors, homoscedasticity, outliers and the normality of residuals, with all assumptions met. All statistical analysis was performed in SPSS 25.

### 3. Results

Breast movement reduction ranged from 36% to 74%, with a mean (SD) of 58% (9) (Figure 3). Breast support level tertiles were identified as low support,  $<54\%$ ; medium support,  $\geq 54\%$  and  $\leq 63\%$ ; high support,  $>63\%$  breast movement reduction. Thirty-four sports bras were assigned to the low support tertile, 35 to the medium support tertile and 29 to the high support tertile. In terms of the brand-classified breast support levels, 11/98 (11%) sports bras tested were identified as low support, 29/98 (30%) were identified as medium support, 46/98 (47%) were identified as high support and 12/98 (12%) were identified as prototype/undefined support (Figure 3). Eighty-two percent of sports bras brand-classified as low support were assigned to the low support tertile (9/11), 45% of sports bras brand-classified as medium support were assigned to the medium support tertile (13/29) and 69% of sports bras brand-classified as high support were assigned to the high support tertile (25/46). Sports bras identified as prototype/undefined ( $n=12$ ) were found in low, medium and high support tertiles (Figure 3).



the performance of the sports bras. No clear trend was evident in neck drop with high, medium and low neck drop interspersed across top, middle and bottom performing category combinations. Underband closure location and type were dominated by back and hook and eye, making the effect difficult to determine.

**Table 3. Mean (SD) breast movement reduction (%) for each of the 58 combinations of sports bra categories, identified in ninety-eight sports bras.**

Mean (SD)* breast movement reduction [%]	Number of bras	1. Bra style	2. Underwire presence	3. Shoulder strap adjustability	4. Shoulder strap configuration	5. Principal fibre content	6. Underband adjustability	7. Cup padding presence	8. Underband closure type	9. Underband closure location	10. Neck drop
74 (7)	1	Combination	Underwire	Adjustable straps	Cross back	Nylon	Adjustable underband	Cup padding	Hook and eye	Back	Low
73 (5)	1	Combination	Underwire	Adjustable straps	Racerback	Nylon	Adjustable underband	No cup padding	Hook and eye	Back	Medium
72 (9)	1	Combination	No underwire	Adjustable straps	Racerback	Polyester	Adjustable underband	Cup padding	Hook and eye	Back	Medium
72 (7)	1	Encapsulation	No underwire	Adjustable straps	Cross back	Nylon	Adjustable underband	Cup padding	Hook and eye	Back	Low
71 (5)	1	Combination	No underwire	Adjustable straps	Cross back	Polyester	Adjustable underband	Cup padding	Hook and eye	Back	High
71 (9)	1	Encapsulation	No underwire	Adjustable straps	Racerback	Polyester	Adjustable underband	Cup padding	Hook and eye	Back	Low
70 (7)	1	Combination	No underwire	Adjustable straps	Cross back	Polyester	Adjustable underband	Cup padding	Hook and eye	Back	Low
69 (7)	1	Combination	No underwire	Adjustable straps	Straight straps	Nylon	Adjustable underband	Cup padding	Hook and eye	Back	High
69 (10)	1	Combination	No underwire	Adjustable straps	Straight straps	Nylon	Adjustable underband	Cup padding	Hook and eye	Back	Medium
69 (8)	1	Combination	No underwire	Adjustable straps	Straight straps	Polyester	Adjustable underband	Cup padding	Hook and eye	Back	Medium
69 (7)	1	Combination	No underwire	Adjustable straps	Cross back	Nylon	Adjustable underband	Cup padding	Hook and eye	Back	High
69 (9)	1	Combination	No underwire	Adjustable straps	Straight straps	Nylon	Adjustable underband	Cup padding	Hook and eye	Back	Low
68 (7)	1	Combination	No underwire	Non-adjustable straps	Cross back	Polyester	Adjustable underband	Cup padding	G hook and loop	Back	Low
68 (8)	2	Combination	No underwire	Adjustable straps	Cross back	Nylon	Adjustable underband	Cup padding	Hook and eye	Back	Medium
67 (9)	1	Combination	No underwire	Adjustable straps	Cross back	Nylon	Non-adjustable underband	Cup padding	Zip	Front	Medium
67 (11)	1	Combination	No underwire	Adjustable straps	Racerback	Polyester	Adjustable underband	No cup padding	Hook and eye	Back	High
67 (9)	1	Combination	No underwire	Adjustable straps	Racerback	Nylon	Adjustable underband	Cup padding	Hook and eye	Back	Low
67 (7)	1	Combination	No underwire	Adjustable straps	Cross back	Nylon	Non-adjustable underband	Cup padding	Zip	Front	High
66 (7)	1	Encapsulation	No underwire	Non-adjustable straps	Cross back	Nylon	Adjustable underband	Cup padding	Hook and eye	Back	Low
66 (5)	1	Encapsulation	No underwire	Adjustable straps	Straight straps	Nylon	Adjustable underband	Cup padding	Hook and eye	Back	Medium
65 (8)	1	Combination	No underwire	Non-adjustable straps	Racerback	Polyester	Adjustable underband	Cup padding	G hook and loop	Side	High
65 (12)	1	Combination	Underwire	Adjustable straps	Racerback	Polyester	Adjustable underband	Cup padding	Hook and eye	Back	Low

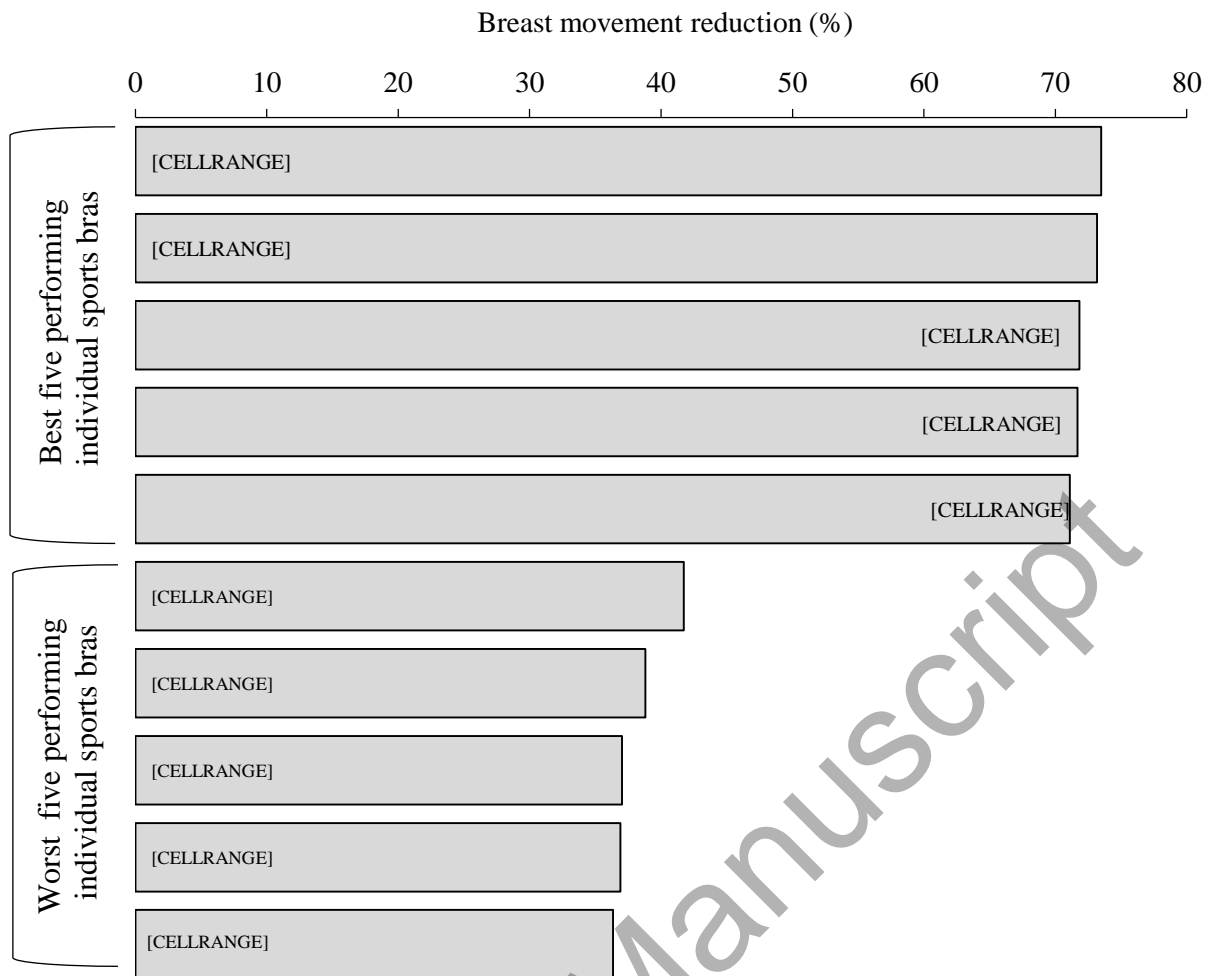
64 (8)	1	Combination	No underwire	Adjustable straps	Straight straps	Polyester	Adjustable underband	Cup padding	Hook and eye	Back	Low
64 (7)	2	Encapsulation	Underwire	Adjustable straps	Cross back	Nylon	Adjustable underband	No cup padding	Hook and eye	Back	Low
64 (8)	3	Combination	No underwire	Adjustable straps	Racerback	Nylon	Adjustable underband	No cup padding	Hook and eye	Back	High
64 (10)	1	Compression	No underwire	Adjustable straps	Racerback	Nylon	Adjustable underband	No cup padding	Hook and eye	Back	High
63 (9)	1	Combination	No underwire	Adjustable straps	Cross back	Polyester	Non-adjustable underband	Cup padding	Not applicable	Not applicable	Medium
63 (9)	3	Combination	No underwire	Adjustable straps	Straight straps	Nylon	Adjustable underband	No cup padding	Hook and eye	Back	High
62 (9)	1	Compression	No underwire	Adjustable straps	Cross back	Polyester	Adjustable underband	Cup padding	G hook and loop	Back	Medium
62 (9)	2	Encapsulation	No underwire	Adjustable straps	Racerback	Nylon	Adjustable underband	Cup padding	Hook and eye	Back	Low
62 (7)	3	Encapsulation	Underwire	Non-adjustable straps	Racerback	Polyester	Adjustable underband	Cup padding	Hook and eye	Back	Low
61 (7)	1	Combination	No underwire	Non-adjustable straps	Racerback	Polyester	Non-adjustable underband	Cup padding	Not applicable	Not applicable	Medium
61 (8)	1	Combination	No underwire	Adjustable straps	Straight straps	Polyester	Adjustable underband	No cup padding	Hook and eye	Back	Medium
60 (10)	4	Compression	No underwire	Non-adjustable straps	Racerback	Nylon	Non-adjustable underband	No cup padding	Not applicable	Not applicable	High
60 (9)	2	Encapsulation	Underwire	Adjustable straps	Straight straps	Nylon	Adjustable underband	No cup padding	Hook and eye	Back	Low
59 (7)	1	Combination	No underwire	Adjustable straps	Racerback	Polyester	Adjustable underband	Cup padding	G hook and loop	Side	Low
57 (7)	1	Compression	No underwire	Non-adjustable straps	Racerback	Polyester	Non-adjustable underband	Cup padding	Not applicable	Not applicable	High
57 (10)	3	Combination	No underwire	Adjustable straps	Straight straps	Polyester	Adjustable underband	No cup padding	Hook and eye	Back	High
56 (9)	1	Compression	No underwire	Adjustable straps	Straight straps	Nylon	Adjustable underband	Cup padding	Hook and eye	Back	Medium
55 (10)	2	Compression	No underwire	Non-adjustable straps	Cross back	Nylon	Non-adjustable underband	Cup padding	Not applicable	Not applicable	Medium
55 (10)	1	Compression	No underwire	Adjustable straps	Cross back	Nylon	Non-adjustable underband	Cup padding	Not applicable	Not applicable	Low
54 (10)	5	Compression	No underwire	Non-adjustable straps	Racerback	Polyester	Non-adjustable underband	Cup padding	Not applicable	Not applicable	Medium
54 (6)	1	Combination	No underwire	Non-adjustable straps	Cross back	Polyester	Non-adjustable underband	Cup padding	Not applicable	Not applicable	Low
54 (9)	1	Compression	No underwire	Adjustable straps	Racerback	Polyester	Adjustable underband	Cup padding	Hook and eye	Back	Low
53 (7)	1	Compression	No underwire	Adjustable straps	Cross back	Nylon	Non-adjustable underband	Cup padding	Not applicable	Not applicable	Medium
53 (8)	2	Compression	No underwire	Non-adjustable straps	Straight straps	Polyester	Non-adjustable underband	Cup padding	Not applicable	Not applicable	Medium
53 (9)	1	Compression	No underwire	Non-adjustable straps	Racerback	Nylon	Adjustable underband	No cup padding	Hook and eye	Back	-
51 (9)	7	Compression	No underwire	Non-adjustable straps	Racerback	Polyester	Non-adjustable underband	No cup padding	Not applicable	Not applicable	Medium
51 (9)	3	Compression	No underwire	Non-adjustable straps	Cross back	Polyester	Non-adjustable underband	Cup padding	Not applicable	Not applicable	Medium
51 (11)	1	Compression	No underwire	Non-adjustable straps	Racerback	Nylon	Adjustable underband	No cup padding	Hook and eye	Back	Medium
51 (8)	7	Compression	No underwire	Non-adjustable straps	Racerback	Polyester	Non-adjustable underband	No cup padding	Not applicable	Not applicable	High
50 (11)	2	Compression	No underwire	Non-adjustable	Racerback	Nylon	Non-adjustable	Cup padding	Not applicable	Not applicable	High



48 (11)	1	Compression	No underwire	Adjustable straps	Racerback	Nylon	Non-adjustable underband	No cup padding	Not applicable	Not applicable	Low
46 (14)	1	Combination	No underwire	Non-adjustable straps	Cross back	Polyester	Non-adjustable underband	Cup padding	Not applicable	Not applicable	Medium
45 (8)	2	Compression	No underwire	Non-adjustable straps	Racerback	Polyester	Non-adjustable underband	No cup padding	Not applicable	Not applicable	Low
42 (10)	2	Compression	No underwire	Adjustable straps	Cross back	Polyester	Adjustable underband	Cup padding	G hook and loop	Back	Low
38 (7)	2	Compression	No underwire	Adjustable straps	Cross back	Polyester	Non-adjustable underband	No cup padding	Not applicable	Not applicable	Low
37 (9)	2	Compression	No underwire	Adjustable straps	Racerback	Polyester	Non-adjustable underband	No cup padding	Not applicable	Not applicable	Low

\*Note: SD represents the standard deviation across participants where only one sports bra was identified and the standard deviation across participants and sports bras where more than one sports bra was identified.

The best performing individual sports bra (74% breast movement reduction) was a combination style bra with underwire, adjustable, cross back shoulder straps, nylon as the principal fibre content, an adjustable underband, cup padding, hook and eye underband closure at the back of the bra and a low neck drop (Figure 4). The worst performing individual sports bra (36% breast movement reduction) was a compression style bra with no underwire, adjustable cross back shoulder straps, polyester as the principal fibre content, a non-adjustable underband, no cup padding and a low neck drop. The most common characteristics within the best five performing individual sports bras were adjustable shoulder straps, an adjustable underband and hook and eye closure at the back. The most common characteristics within the worst five performing individual sports bras were a compression style, no underwire, adjustable shoulder straps, polyester principal fibre content, and a low neck drop (Figure 4).



**Figure 4. Best five performing and worst five performing individual sports bras, identified by breast movement reduction (%), and their associated characteristic categories.**

**Figure 4 Alt Text. A bar chart displaying the sports bra characteristics associated with the best and worst performing sports bras.**

### 3.2 Multiple regression

The stepwise procedure terminated after 8 iterations and a significant regression equation was found

( $F_{(10,1150)} = 71.562, p < 0.001$ ), with an  $R^2$  of 38.4 (Table 4).

**Table 4. Summary of multiple regression analysis (8<sup>th</sup> model iteration)**

Variable	<i>B</i>	<i>SE<sub>B</sub></i>	<i>β</i>	p
Intercept	42.14	5.03		<0.01
<i>Bra style</i>				
Compression	reference			
Encapsulation	8.53	1.32	0.24	<0.01
Combination	9.89	0.90	0.39	<0.01
BMI	0.86	0.17	0.12	<0.01
<i>Underband adjustability</i>				
Adjustable underband	reference			
Non-adjustable underband	-4.69	0.97	-0.19	<0.01
<i>Principal fibre content</i>				
Polyester	reference			
Nylon	3.96	0.66	0.16	<0.01
<i>Cup padding presence</i>				
No cup padding	reference			
Cup padding	3.64	0.62	0.15	<0.01
Neck drop	-0.79	0.17	-0.15	<0.01
<i>Underwire presence</i>				
Underwire	reference			
No underwire	-2.56	1.25	-0.06	0.04
<i>Shoulder strap adjustability</i>				
Adjustable straps	reference			
Non-adjustable straps	2.34	0.85	0.10	0.01
<i>Shoulder strap configuration</i>				
Racerback	reference			
Straight straps	-2.06	0.81	-0.07	0.01

Note: *B* = unstandardised regression coefficient; *SE<sub>B</sub>* = standard error of the coefficient; *β* = standardised regression coefficient

The final three characteristics added within iterations 6, 7 and 8 (underwire presence (underwire to no underwire), shoulder strap adjustability (adjustable straps to non-adjustable straps) and shoulder strap configuration (racerback to straight straps) of the stepwise procedure only accounted for an additional 1.3% of the variation in breast movement reduction (%), and therefore the 5<sup>th</sup> iteration was identified as the most parsimonious model. Therefore, a final significant regression equation was identified ( $F_{(7, 1153)} = 97.074$ ,  $p < 0.001$ ), with an  $R^2$  of 37.1 (Table 5). The standardised regression coefficients suggest that a bra style of either encapsulation or combination result in the largest increase in breast movement reduction (%), followed by padding in the 5<sup>th</sup> iteration model.

**Table 5. Summary of multiple regression analysis (5<sup>th</sup> model iteration)**

Variable	<i>B</i>	<i>SE<sub>B</sub></i>	<i>β</i>	p
Intercept	38.28	4.55		<0.01
<i>Bra style</i>				
Compression	reference			
Encapsulation	10.08	1.23	0.28	<0.01
Combination	9.38	0.87	0.37	<0.01
BMI	0.91	0.17	0.12	<0.01
<i>Cup padding presence</i>				
No cup padding	reference			
Cup padding	3.75	0.60	0.15	<0.01
<i>Principal fibre content</i>				
Polyester	reference			
Nylon	3.39	0.63	0.14	<0.01
<i>Underband adjustability</i>				
Adjustable underband	reference			
Non-adjustable underband	-3.05	0.86	-0.13	<0.01
Neck drop	-0.75	0.15	-0.14	<0.01

Note: *B* = unstandardised regression coefficient; *SE<sub>B</sub>* = standard error of the coefficient; *β* = standardised regression coefficient

Breast movement reduction (%) was predicted as  $38.28 + 10.08$  (bra style (compression to encapsulation)) +  $9.38$  (bra style (compression to combination)) +  $0.91$  (BMI) +  $3.75$  (cup padding presence (no cup padding to cup padding)) +  $3.39$  (principle fibre content (polyester to nylon)) –  $3.05$  (underband adjustability (adjustable underband to non-adjustable underband)) -  $0.75$  (neck drop). Breast movement reduction (%) increased by 0.91% for each unit increase in BMI and as the neck drop lowered, breast movement reduction (%) decreased by 0.75% for each centimetre.

#### 4. Discussion

This study measured breast movement reduction (%) during running to investigate the performance of a large sample of sports bras. We aimed to use this large sample to present the first estimate of breast movement reduction tertiles representing low, medium and high breast support, and compare these outcomes to the sports bras brand-classified breast support level. Lastly, this study aimed to investigate the affect of ten sport bra characteristics on sports bra performance during running, utilising breast movement reduction as a surrogate sports bra performance measure. Breast movement

reduction ranged from 36% to 74% across the 98 sports bras tested. The values reported are similar to those previously reported (Scurr et al. (2011) for D cup females (59%) and Boschma et al. (1994) for B and C cup females (53% and 64% respectively). However, >70% breast movement reduction for a sports bra has not been previously reported in research, which may reflect an improving sports bra market. Bowles et al. (2012) suggested that advancements in design and textile technology are contributing to an ever-evolving sports bra market, with more complex sports bra designs. The lower values of breast movement reduction reported in this study (<40%) were also lower than any previously reported in research. The current study utilised running, a high intensity exercise (Forsyth and Roberts, 2018), to assess breast movement reduction. Typically, a high support sports bra is recommended for running (McGhee et al. 2013; White et al. 2015), however low and medium support sports bras, along with prototype/undefined sports bras were included within this study, and may therefore account for these lower breast movement reduction values.

In 2008 Bowles et al. (2008) suggested that an international standard for sports bras was required to ensure females can easily identify sports bras which provide adequate support. This study assigned breast movement reduction values to low, medium and high breast support tertiles, providing the first estimate of sports bra performance levels against which the sports bra industry can market and compare their products. It is acknowledged that these tertiles only represent the performance of the range of sports bras tested in this study. Additional testing would add further data, which may change the values associated with each tertiles. However, with nothing else available, the bra industry is likely to be using an approach which is not data driven and open to inconsistency. Therefore, the authors offer this method as a starting point upon which additional data can be added.

Zhou et al. (2013) suggested that brand-classified high support sports bras may not actually provide effective control of breast movement, interestingly 69% of the brand-classified high support bras were correctly classified. The majority of brand-classified low support bras were also correctly classified (82%), but this was not observed with the medium support bras where over half (52%) were positioned in low support tertile (<54% breast movement reduction).

Over one-third of variability in sports bra performance was attributed to five sports bra characteristics (bra style, cup padding presence, principal fibre content, underband adjustability and neck drop) and participants BMI. Bra style was the largest contributing characteristic, with a change from compression to encapsulation, or a change from compression to combination resulting in a ~10% improvement in performance. Previous investigations into the affect of bra style on sports bra performance have reported mixed results; Starr et al. (2005) compared a prototype combination bra to a combination bra and compression sports bra, and identified that the prototype combination bra outperformed during running. However, White et al. (2011) identified no difference in breast movement (assessed using vertical breast displacement) between compression and encapsulation sports bras during running, and therefore recommended the use of either bra when running, as opposed to no support.

While padding within a sports bra may be used for modesty, shaping and/or protection (Lorentzen and Lawson, 1987; Zhou et al. 2011), the current study suggests that padding also reduces breast movement, improving sports bra performance. Previously, McGhee and Steele (2010) added foam padding to encapsulation bras to investigate the effect of increased breast elevation and compression on breast displacement and discomfort. However McGhee and Steele (2010) found that the addition of padding did not significantly alter vertical breast displacement during running. McGhee and Steele (2010) classified the bras within their study as high support and therefore it is possible that in terms of limiting vertical breast displacement these bras were already performing highly, without padding. The sports bras within the current study were low, medium and high support and therefore the presence of padding in certain bras may have had a greater effect on performance.

When investigating principal fibre content, a change from polyester to nylon improved sports bra performance by 3.39%. This contradicts previous research; Zhou et al. (2013) identified that a bra composed of 91% polyester fibre outperformed bras composed of primarily nylon. However, the bras examined by Zhou et al. (2013) also varied in terms of brand-classified support levels and bra styles,

and therefore a reduction in breast displacement may have been effected by differences in other characteristics. Yu and Zhou (2016) identified that polyester and nylon both possess identical properties in terms of elasticity (high), stretch ability (high), recovery (high), strength (high), and comfort (low), therefore, it may be the interaction of the principal fibres with the remaining sports bra fibres and the sports bra style which contribute to differences in sports bra performance.

A change from an adjustable underband to a non-adjustable underband resulted in a 3.05% decrease in sports bra performance. While sports bra underband adjustability aids donning and doffing (Krenzer et al. 2005), there was little information regarding the contribution of underband adjustability to sports bra performance. Adjustability in the underband means it can be lengthened or opened when donning and doffing, and shortened when in place. The shoulders are usually wider than the chest where the underband will ultimately sit and therefore to enable donning and doffing without adjustability the underband needs to be long enough or stretchy enough to be pulled over the shoulders. This is the first study to suggest that a lack of adjustability in the underband may compromise the breast movement reduction achieved by the sports bra. Bowles et al. (2012) reported that perceived tightness of sports bras around the chest was a deterrent to sports bra use during exercise and therefore an adjustable underband may not only improve the performance of the sports bra, but may also improve comfort and increase sports bra use.

Neck drop was the final sports bra characteristic to affect sports bra performance, with an increase in neck drop (lowering of the neckline by centimetre) resulting in 0.75% decrease in sports bra performance. A high neck drop has long been identified as an important feature in affective sports bras (Page and Steele, 1999), with Zhou et al. (2012) suggesting that a high neck drop should be utilised in sports bras to apply compression to the upward boundary of the breast, preventing upward movement. Furthermore, Zhou et al. (2009) identified that a high neck drop also increases the shock absorbing properties of a sports bra during running.

Underwire presence, shoulder strap adjustability and shoulder strap configuration showed minimal effect on sports bra performance. While Bowles et al. (2008) identified that Australian females perceived underwire as a “very important feature” when selecting a sports bra, the current findings suggest that underwire may not affect sports bra performance. Within the current study all participants were bra fitted prior to data collection, and underband and shoulder straps were adjusted where possible. This may have influenced the potential effect that shoulder strap adjustability may have had. The ability to alter shoulder strap length may be of greater importance in ill-fitting sports bras. While shoulder strap configurations such as racerback and cross strap provide a feeling of reassurance during physical activity (Bowles and Steele, 2013; Yu and Zhou, 2016), it is possible they do not perform differently.

The current study identified that five sports bra characteristics contributed to over one-third (37.1%) of variation observed in sports bra performance, however, nearly two-thirds (62.9%) was unaccounted. There are a number of variables that may contribute to this; previous research has identified that individual running styles may contribute to breast movement (White et al. 2015) and females adopt mechanical alterations to their gait (Shivitz, 2001) and trunk displacement (Boschma et al. 1994) dependent on breast support levels. Whilst running speed was controlled, participants running style was not and gait kinematics were not measured. It is therefore possible that changes in participants running style contributed to variation across sports bra trials. Additionally, further sports bra characteristics not included may affect performance, including shoulder strap width and shoulder strap tightness. Previously, Colman et al. (2015) investigated alterations in shoulder strap width and identified that wide, vertical, padded straps performed best in terms of strap pressure and comfort. Within the current study shoulder strap width and tightness, along with underband width and tightness were not measured, and it is possible these may also affect sports bra performance. While the current study recruited participants aged between 18 and 36 years, who had not given birth or breast-fed within the last 12 months, had not undergone any surgical procedures to their breasts and were a 34B or 34D bra size, this is not wholly reflective of the sports bra market consumer group. Future research should expand on this participant grouping, particularly focusing on women with larger breast sizes



(D+ cup size), as women with larger breast may experience musculoskeletal pain and poor posture, particularly when wearing inadequate breast support (McGhee et al. 2013). Lastly, while previously subjective variables such as breast pain (Nolte et al. 2015; Risius et al. 2017) and bra comfort (Nolte et al. 2015; Risius et al. 2017) have been identified as important outcome measures in relation to sports bra performance, it was decided within the current study to focus on objective sports bra performance (breast movement reduction). Future research could incorporate subjective measures of sports bra performance to gain a holistic understanding of the sports bra market.

## **Conclusions**

The current study identified that, in the 98 sports bras tested, breast movement reduction ranged from 36% to 74%, with 69% of the brand-classified high support sports bras analysed within the current study were positioned within the high support tertile (>63% breast movement reduction). Additionally, the sports bra characteristics which improve sports bra performance (as measured by an increase in breast movement reduction from the reference category) are; an encapsulation bra style (+10.08%), with cup padding (+3.75%), nylon as the principal fibre content (+3.79%), an adjustable underband (+3.05%), and a high neck drop (+0.75%, with every centimetre increase toward a high neckline). These results may facilitate the sports bra industry with the development of high-performance sports bras, increasing sports bra satisfaction and ultimately reducing the barrier which the breast may play in sport and exercise participation.

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