Sports bras and breast kinetics

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8.1 Introduction

The female breast contains limited anatomic support because of a lack of muscles and bones. Excessive movement during activities produces large forces on the breasts that result in stretching of the Cooper ligaments, discomfort, pain, and embarrassment and/or cause the breasts to sag. As a consequence, over time the breasts may lose their natural perkiness; this may also affect breast aesthetics and, ultimately, a subject's health. A recent survey in the United Kingdom found that only 10% of the school girls reported always wearing a sports bra during sport and exercise, whereas half reported never wearing one (Scurr et al., 2016). Therefore, education of the young generations on the proper use of bras is confirmed as being necessary.

Previous studies have verified that sports bras are more effective in limiting breast motion and reducing breast discomfort compared with everyday bras (Okabe and Kurokawa, 2005). The results have largely been obtained through empirical studies, but there is relatively little published information on the interaction of the components within a sports bra or how to improve the design of sports bras for controlling breast movement.

Improving the functional design of sports bras requires the scientific study of three-dimensional (3D) breast movement for different breast sizes and shapes. Previous studies investigated the effectiveness of different styles of bras made from different materials (Scurr et al., 2010). Their design rules have yet to emerge, however, and the scientific methodology to establish their design criteria has yet to be proposed. This chapter provides an overview of the features and functions of sports bras, the kinetics of female breasts, and the design criteria for sports bras.

8.2 Structure and function of sports bras

8.2.1 *Types and features of sports bras*

Traditionally, sports bras are classified into two different types: compression and encapsulation (Yu et al., 2006) (Fig. 8.1). A compression bra is designed to restrict movement of the breasts by compressing and flattening them against the body, which decreases the force moment arising from breast movement. An encapsulation bra contains two individual cups that separate and support the two breasts.

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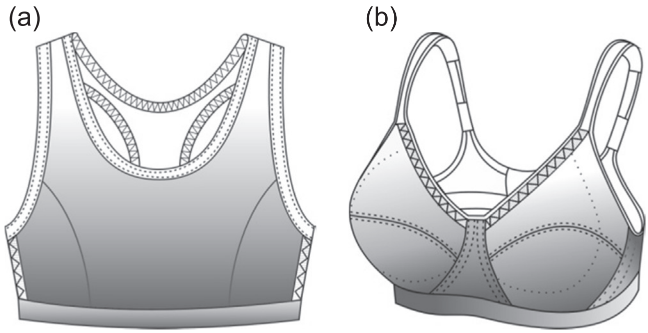

Figure 8.1 Two types of sports bras: (a) compression bra; (b) encapsulation bra.

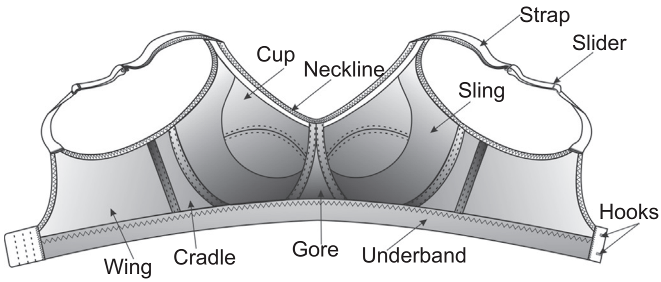

Figure 8.2 Garment structure of an encapsulation bra.

A compression bra generally has a higher neckline to restrict the upward movement of the upper breast, and wider shoulder straps to distribute the pressure over the shoulders to larger back panels. However, the compression force acting on the breast may also cause breast discomfort and distort the breast shape.

On the other hand, as shown in Fig. 8.2, an encapsulation bra has a gore and two cups. The gore separates the two breasts and the cups hold the breasts in place, so the breast shape is less distorted. The gore cannot be set too high, so an encapsulation bra has less control of upward breast movement than a compression bra. However, a sling can be placed at the side of the inner cup in an encapsulation bra, which is perceived to be more effective in limiting lateral breast movement.

One study (Page and Steele, 1999) has claimed that compression bras are more effective for women with smaller breasts (cup sizes A or B), whereas encapsulation bras are more effective for the women with a cup size C or above, but this was not confirmed by experimental data. By contrast, White et al. (2009) found no significant differences between the two types of sports bras in controlling breast movement. A significant limitation in their study was that they only used one compression bra and one encapsulation bra to compare the effectiveness of the bras in controlling breast movement. These findings need to be verified further by experiments performed while subjects wear the bras. Many factors such as bra material, height of the neckline, shoulder strap design, and their physical and mechanical properties may influence the effectiveness of sports bras, so a detailed examination of bra features is necessary.

Table 8.1 Properties of the fibers used in sports bras

Properties	Fiber			
	Cotton	Spandex (Lycra)	Polyamide (Nylon)	Polyester
Elasticity	Low	High	High	High
Stretch ability	Low	High	High	High
Recovery	Low	High	High	High
Strength	High	Low	High	High
Comfort	High	High	Low	Low

Adapted from Shishoo, R. ed., 2005. Textiles in sport. Elsevier.

8.2.2 Fiber content in sports bras

Currently, commercial sports bras typically contain elastane, polyamide, or polyester fibers. These are lightweight with good strength and resistance to abrasion; they are easy to wash, are dimensionally stable, and dry quickly. The properties of these fibers in contrast with cotton are shown in Table 8.1. Although conventional polyester fiber cannot provide the high-level comfort cotton does, Coolmax with a specific cross section can significantly improve the comfort performance in terms of moisture wicking.

8.2.3 Fabrics in sports bras

Sports bras commonly use knitted fabric. The intermeshing loops of yarn containing spandex allow large extensibility and a high recovery rate. Multiway stretchability is preferred since sports bra fabrics must be able to extend greatly in both wale and course directions. However, previous work on sports bras seldom investigated the effects of fabric structure. Lawson and Lorentzen (1990) mentioned the modulus and elasticity of knitted fabrics, but no test data were provided. Lu et al. (2016) recently studied fabric deformation in biaxial extension as a plane stress problem in elastic mechanics using Eq. [8.1].

$$\begin{bmatrix} F_1 \\ F_2 \\ F_{12} \end{bmatrix} = \begin{bmatrix} \frac{E_1}{1-v_1v_2} & \frac{v_2E_1}{1-v_1v_2} & 0 \\ \frac{v_1E_2}{1-v_1v_2} & \frac{E_2}{1-v_1v_2} & 0 \\ 0 & 0 & G \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_{12} \end{bmatrix} \tag{8.1}$$

where F is the tensile stress, ε is the tensile strain, E is Young's modulus, and v is Poisson ratio. The subscripts 1 and 2 denote the wale and course directions, respectively. The mechanical properties of the two fabrics under investigation are shown in Table 8.2.

Table 8.2 Poisson ratios and Young's modulus of sports bra fabrics (Lawson and Lorentzen, 1990)

	v_1	v_2	E_1/(N m^{-1})	E_2/(N m^{-1})
Warp knit fabric	0.17	0.09	3.15	2.26
Weft knit fabric	0.24	0.23	1.23	1.98

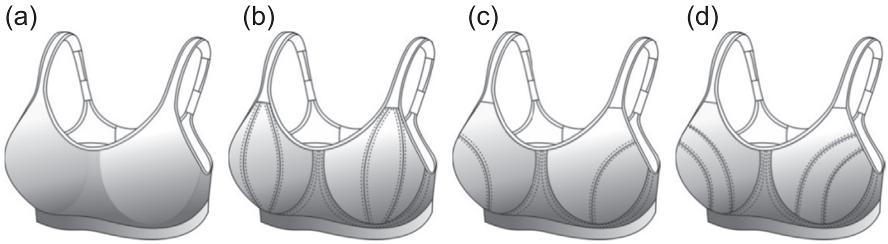

Figure 8.3 Sports bras with different types of cup seams: (a) seamless; (b) double vertical seam; (c) bias seam; and (d) double bias seam.

8.2.4 Components of sports bras

As shown in Fig. 8.2, the components of an encapsulation sports bra include cups, straps, a gore, an underband, back wings, a cradle, and fasteners (hooks). Commercial sports bras mainly vary in the design of their bra cups, straps, and backs.

8.2.4.1 Bra cups

Both compression and encapsulation sports bras use a design with a high neckline to prevent upward breast movement. As shown in Fig. 8.3, the cups in sports bras mostly have full coverage but can either be seamless or made in various cut-and-sewn styles.

There are three main types of seam construction used in bra cups—namely, horizontal, vertical, and bias. Molded cups have a simple and smooth appearance, but provide less control of breast movement because of gaps between the breast and bra that easily appear inside the cup. Cut-and-sewn cups may fit the breasts better and more effectively control medial-lateral breast movement, but scientific evidence to support this perception is lacking.

8.2.4.2 Shoulder straps and back designs

The shoulder straps of bras are essential to support the breast mass and hold the breast in place with limited breast movement. Most shoulder straps of sports bras are wider than those used in everyday bras to distribute the breast mass across a greater area in the back panel and reduce pressure on the shoulders. Current sports bras tend to use padded straps to dissipate the energy produced by the breast mass and velocity during movement.

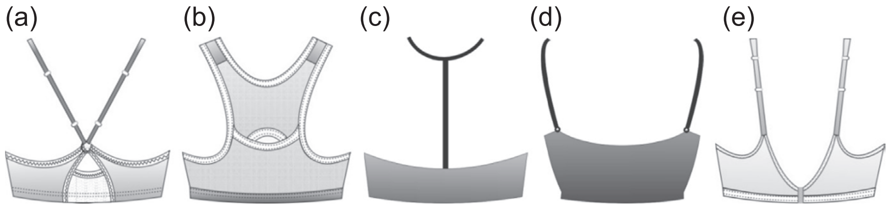

Figure 8.4 Five back designs of sports bras: (a) crossover; (b) racer back; (c) vertical center; (d) straight back, and (e) U-back.

There are five main back designs for sports bras: crossover, racer back, vertical center, straight back, and U-back (Fig. 8.4). Styles of crossover, racer back, and vertical center designs can prevent the straps from slipping off the shoulders during activities. Sports bras with a straight back or U-back are anticipated to be more effective than the other three types of back designs in reducing vertical breast movement because the force direction acting on these shoulder straps is more aligned with the direction of breast gravity.

8.2.5 *Functions of sports bras*

Sports bras are sturdier than everyday bras; they allow the breasts to move in unison with the trunk, not separately, thus reducing the chances of damage to the ligaments in the breast during high-impact exercises such as jogging. A good sports bra should provide adequate support by restricting breast motion in the hope that, for example, the reduction of discomfort might promote motivation to remain in a fitness program (Shivitz, 2001).

A well-fitting sports bra might prevent sports-induced breast discomfort, pain, and even injury. However, to allow their breast tissues to grow naturally, younger girls should not routinely wear sports bras. If breast discomfort occurs, however, a sports bra could be helpful in preventing pain during breast growth and in managing acute sports-induced pain (Hadi, 2000).

8.3 Kinetics of female breasts

A woman's body is exposed to repetitive impact loading during physical activity. When the feet hit the ground, impact forces (shocks) develop throughout the body (Zadpoor et al., 2007). The impact force acting on the feet is influenced by many factors, including the inertia and masses of various body segments involved in the acceleration and deceleration processes, joint angles between body segments, the coupling between soft and rigid masses, and joint stiffness (Nigg and Liu, 1999). With each foot strike on the ground during jogging, a shock wave is transmitted throughout the body. Vance et al. (2002) reported that the magnitude of the impact wave reduces as it travels along the leg to the head; this is known as shock

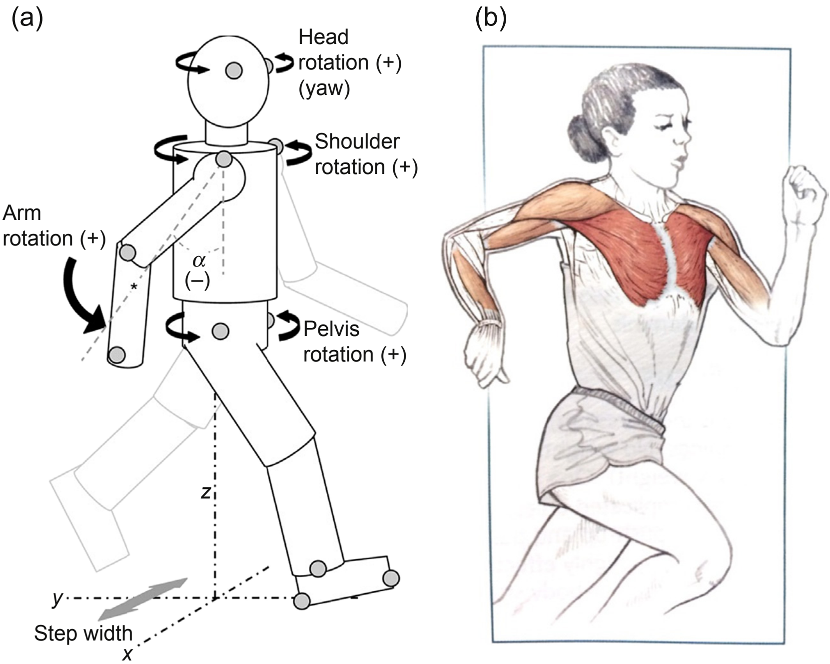

Figure 8.5 Joint rotation (a) and arm swing (b) in human walking and running.
Pontzer, H., Holloway, J.H., Raichlen, D.A., Lieberman, D.E., 2009. Control and function of arm swing in human walking and running. Journal of Experimental Biology 212, 523–534.

attenuation. Shock attenuation is brought about by the shock absorbers within the human body, such as joint positioning (Bobbert et al., 1992), muscle activity (Christina et al., 2001), synovial fluid, bone, and articular cartilage. When the force is not absorbed by the lower extremities, it is transmitted up a kinetic chain to exert a force on the pectoralis major muscle within the chest. The force of gravity acting through the breasts and the force that acts on the pectoralis major muscle largely contribute to initiating breast movement.

To maintain stability during running, the arms swing to counteract the vertical body moments imparted by the swinging legs. As shown in Fig. 8.5, the arm moments serve to cancel lower-limb moments about the body's vertical axis. Each arm movement is driven by the biceps and triceps that connect with the pectoralis muscles, which bring the breasts upward with potential energy countering the gravity force.

8.4 Previous work on breast movement

During exercise, breasts move in complex 3D motions. A better understanding of breast motion both braless and constrained by sports bras will contribute to the development of women's sports bras. The number of publications on breast motion has increased notably during the past decade. However, the various methods used to study breast motion have generated some inconsistent findings. The bra types studied include sports bras, everyday bras, and crop tops. However, very few papers have included images of or detailed specifications for the styles and constituent materials of the bra samples used in the studies. Consequently, the discussions regarding previous investigations into breast movement have largely been based on unspecified garment parameters and uncontrolled material properties.

8.4.1 Types of activities

The types of activities reported in breast motion studies have mainly been walking, running, jogging, and aerobics. The walking speeds in the studies have ranged from 4.83 to 7 km/h; the running/jogging speeds ranged from 6 to 13 km/h.

8.4.2 Motion-capturing equipment

As video motion-capture technology has become more developed, preconfigured and precalibrated motion analysis systems (ProReflex, Oqus, and Vicon) have evolved and have enabled the convenient use of 3D coordinate systems for measuring motion. The collected 3D raw data can be readily processed using supplier-provided programs (Scurr et al., 2011). However, the accuracy of breast movement data could be affected by the motion-capturing equipment, the number of study points on the breasts, the location and number of reference points, and the reference systems.

8.4.3 Breast displacement

Evidence from early studies (Starr et al., 2005) showed that the vertical displacement of breasts in compression bras was larger than that measured in encapsulation bras. Consequently, it was believed that encapsulation bras were more effective in reducing breast movement than compression bras. However, McGhee and Steele (2010) challenged this claim; they found no significant difference in breast constraint between these types of bras. The effectiveness of the sports bras in reducing breast movement involves many factors, such as fabric elasticity and breast stiffness. In these early studies, however (Pontzer et al., 2009), the above factors were not well controlled, so the findings need to be compared with reservations.

According to White et al., the mean breast displacement measured in their studies was largest in a vertical direction because of both the breast inertia and the vertical reaction force generated when the subject's foot hit the ground. The magnitude of the breast inertia depended on the movement of the thorax (leaning back and forth, swinging left and right). Because breast movement in anterior–posterior and medial–lateral directions is mainly caused by only breast inertia, the breast displacement in these directions was smaller than that in a vertical direction.

Most studies have assumed that the left and right breasts are symmetrical, but, in reality, breast asymmetry is more common. The selection of either the left or right breast may be misleading when making recommendations for bra design. Mills et al. (2015) suggested that motion data should be collected for both breasts before deciding whether to present data on both breasts or just the dominant one in case of movement asymmetry.

Previous work has tended to conduct breast motion experiments over a short duration (about 2 min). Few researchers have monitored breast displacement over 5 min. Bowles and Steele (2003) reported significant increases in vertical breast displacement from the first minute to the fourth and fifth minutes of running, which are the result of possible tissue strain after repeated loading of forces on the delicate breast tissues. Milligan et al. (2015) found that during a 5-km run, the multiplanar breast displacement was much greater than during a 5-min run with both low and high levels of breast support. Therefore they advocated that an experimental protocol should incorporate at least 7 min of running to obtain a more representative measure of breast kinematics.

According to Starr et al. (2005), the vertical breast displacement while running wearing a sports bra was only 0.08 cm or less. The level of accuracy was uncertain. By contrast, McGhee and Steele (2010) found that the mean breast displacement was 5.1 cm. The large difference in the breast displacements measured might be the result of different breast sizes, breast stiffness, and running speed, or sports bras with different fabrics. Different reference points and reference systems were chosen in the two studies; this is likely to have significantly influenced the values of displacement obtained.

Overall, the evidence is conclusive that breast displacement is greater when the breasts are braless than when constrained by a sports bra. Therefore women should wear sports bras to limit their breast movement and hence reduce potential breast pain.

8.4.4 Breast comfort

Mason et al. (1999) found that breast pain was related to vertical breast displacement rather than acceleration, whereas another study (Scurr et al., 2011) showed that increased comfort was attributed to reduced vertical breast velocity rather than a reduction in displacement. Scurr et al. (2016) also found that breast comfort was highly correlated with breast velocity, but had only moderate relationships with breast displacement and acceleration. Based on the aforementioned findings, breast comfort is related to breast displacement, velocity, and acceleration. Acceleration affects the external forces acting on the breasts during activities.

Lin et al. (2015) investigated local breast skin temperatures in the running state when wearing sports bra made of dynamic moisture-transfer fabrics. They found that the skin temperature was significantly lower than temperature when wearing a bra made of single jersey, although the thermal psychological subjective sensation for the two types of fabrics were very similar. It was confirmed that the use of fabrics with dynamic moisture properties in sports bras could improve thermal comfort.

8.5 Criteria for a well-designed effective sports bra

To evaluate the functions of a sports bra, Haycock (1978) recommended the following criteria:

- good upward support
- limited motion of the breasts relative to the body
- absorptive, nonallergenic, nonabrasive, and mostly nonelastic materials
- well-covered fasteners on both sides to prevent abrasion of the skin
- wide and nonelastic straps that do not slip off the shoulders
- no riding up of the bra over the breasts by a wide cradle or underwire
- pockets inside the bra to enable the placement of padding, if needed

Lawson and Lorentzen (1990) suggested that, for sports or exercises that require substantial amounts of overhead reaching, bra straps should be stretched more than daily bras to prevent the bra from riding up over the breasts. Large cup sizes should incorporate inextensible/inelastic cup fabrics and straps, or those with a very high elastic modulus, that provide support to the entire breast. Designs for women with small breasts could use less restrictive design features and comfortable fabrics.

McGhee and Steele (2010) proposed the inclusion of thick foam pads inside the bra cup to elevate and compress the breasts in an encapsulation sports bra to reduce vertical breast displacement and exercise-induced bra discomfort. In industrial practice, inelastic, thin fabrics in the bottom cup and side sling fabric connected to wide shoulder straps are commonly used to elevate the breasts and distribute the gravitational force from the breasts to the back. To reduce the force moment, a compression style with a high neckline is believed to be more effective (Zhou et al., 2013).

Bowles and Steele (2013) found that the maximum pressures under a bra strap range from 0.83 to 2.67 N/cm^2 during running. A crossed-back strap orientation exerted a higher force and pressure on the shoulder compared with a straight-back design. Bra strap cushions only reduced the pressure in the crossed-back strap orientation, but there was no significant difference in shoulder comfort between different strap orientations.

Zhou et al. (2013) identified the effective design features for commercial sports bras by evaluating the reduction in breast displacement in four subjects performing activities braless and while wearing seven different sports bras. She found a significant difference in breast displacement between the different breast regions, with the greatest reduction in breast displacement (RBD) in the medial-lateral direction, whereas the least RBD was in the top breast region (Fig. 8.6). The RBD was positively related to the gore height, shoulder strap width, neckline height, and side seam depth in the bras.

It was concluded that, of the bras tested, the most effective bra was a compression type with a short vest style, high neckline, side slings, cross-back straps, a bound neckline, no center gore, no wire, no cradle, no pad, and a nonadjustable wide strap.

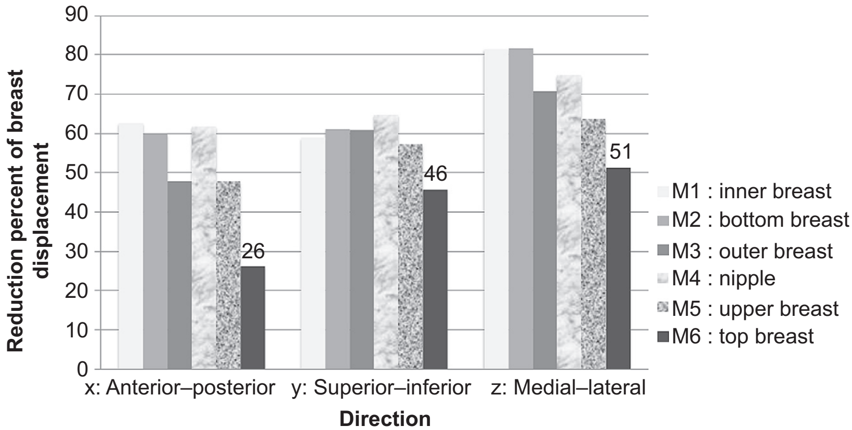

Figure 8.6 Reduction in breast displacement at different breast regions.
Haycock, C.E., 1978. Breast support and protection in the female athlete. In: American Alliance for Health, Physical Education, Recreation, and Dance Consortium Symposium Paper, vol. 1, pp. 50–53.

8.6 Conclusion

This chapter presented a comprehensive overview of the literature on sports bras' effective features and related research on movement within and the thermal comfort of sports bras. Previous work has studied various subjects from 20 to 60 years of age, with bra cup sizes of sizes from B to DD. In addition to sports bras, everyday bras and crop tops have been studied. However, the findings have been based on inadequately specified garment and material parameters and the sports activities largely focused on running; not many other sports exercises involving irregular movement have been researched. Researchers have mainly used nipple movement to represent the movement of the whole breast, and they have tended to focus on breast displacement in the vertical direction.

Not surprisingly, sports bras have been proven to control breast movement while performing physical activities better than everyday bras. Breast displacement has been shown to be largest in the vertical direction during running while braless, especially for subjects with large breasts. Studies of the performance of encapsulation bras compared with compression bras are inconclusive. One study reported that encapsulation bras gave a smaller breast displacement, but two studies found the opposite. The results for vertical breast displacement during running in a sports bra have also varied (from 0.05 to 5.10 cm).

The effects of nonlinear material properties on dynamic breast motion have not been investigated in any great depth. When breast tissue moves over the chest wall, there is internal force acting on the breast tissue. No biomechanical model has yet been developed to simulate the internal force in breast tissues in 3D space. Analysis of breast trajectory and theoretical modeling of breast vibration could provide useful information for the future design of sports bras. Although this is a niche and difficult research area because breasts are viscoelastic in nature and their motion in 3D space is highly complex, it warrants more attention because appropriate support of the breasts is crucial to women's well-being.

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