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BIOMECHANICAL ANALYSIS OF A PROTOTYPE SPORTS BRA

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ABSTRACT

A Latin Square Experimental Design was used to compare a prototype sports bra previously developed for large-busted women, with two other sports bras through a controlled laboratory wear study. Vertical breast displacement data were gathered by videotaping the first three running strides of six large busted active females recruited from local fitness centers. Multiple regression results found that the garment treatment significantly related to the breast displacement experienced by subjects during each test session [F (2,213) = 16.393; p< .0001]. Approximately 13% of the variability in breast displacement was predicted by garment, indicated by the Squared Multiple Correlation Coefficient. ANOVA results found significant subject, garment, and subject-by-garment effects. Subjects wearing garments A and B had a lower level of vertical breast displacement of .031" as compared to subjects wearing garment C with .045" of displacement.

Keywords: biomechanical research, sports bras, brassieres, vertical breast displacement, breast discomfort, female exercise, and human motion.

Introduction

Greater emphasis is being placed on physical fitness, a positive self-image, personal enjoyment, and weight loss. The Surgeon General asks the American people to promote exercise and states that physical activity joins the front ranks of essential health objectives, such as sound nutrition, use of seat belts, and prevention of adverse health effects of tobacco use (U.S. Department of Health and Human Services, 1996). In a September 17, 1998 news release, the American Council on Exercise (ACE) reported a majority of women experience breast discomfort while exercising, causing some to avoid exercise all together. Physical activity causes the breasts to bounce. As the activity increases, so does the bounce and the larger the breasts, the greater the vulnerability. Breast discomfort reported by physically active women is thought to be due to excessive breast displacement (Himmelsbach, J., Valiant, G., Lawson, L., & Eden, K., 1992). Despite the increase of women athletes and the accelerated need to limit breast movement, little scientific research has been conducted in the area of breast motion (Page & Steele, 1999). Better understanding of breast motion during exercise could be seen as a major contribution to the development of a supportive bra and a minor contribution toward encouraging and promoting the participation of women in physical activities and ultimately to leading healthy lifestyles.

Literature Review

Although the size and shape of female breasts vary by person, most breasts are tear shaped. Approximately two-thirds of the breast is composed of breast tissue, while the rest is made up of superficial fascia (fat) tissue, which is what fluctuates as a woman gains or loses weight (Love, 2000). Due to minimal intrinsic structural breast support, breast displacement associated with exercise is difficult to reduce (Hadi, 2000). The only muscle in the breast area lies under each glandular structure. Therefore, breast support is dependent upon weak suspensory ligaments known as Cooper's ligaments. Referring to these fibers as ligaments is misleading, as they are not ligaments that attach muscles to bone or support joints, they are fascial planes that are primarily intended to divide the glandular elements in the breasts into lobules from which ducts drain to the nipple during lactation (Haycock, 1978). Skin, a thin, flexible elastic cover, provides the breast with a secondary support system (Page & Steele, 1999).

Women who wear an average 'B' cup carry 5 to 7 pounds in her breasts, while women wearing an average 'D' cup carry 15 to 23 pounds (Cohen, 2002). Breasts are not immune to the laws of gravity and without proper support, the ligaments and delicate breast tissue will begin to stretch and distend allowing the breast tissue to elongate, developing a pendulous look. Middle age women living in primitive areas of the world where supportive breast garments are not worn, have flattened, pendulous breasts. With advancing age, most women's breasts flatten and elongate, but this happens more quickly when a supportive garment is not worn (Haycock, 1978). When gravity pulls the breasts down, it also pulls the throat and face tissue (The Buststop, 2004).

Through his work in the outpatient department at the King Fahd Hospital of the University, Alkhobar, Kingdom of Saudi Arabia, Dr. Maha Abdel Hadi found breast pain to be a common complaint among his female patients. Dr. Hadi designed a research study where a sample of 200 women presented to the outpatient department with similar symptoms and breast pain, were randomly divided into two groups. The first group of subjects adhered to a drug regimen commonly prescribed to combat these symptoms, while the second group wore sports bras for twelve weeks. All subjects received a survey instrument, designed to assess their response to the given treatment. The response was 100% as all patients willingly followed their specific instructions. Fifty-eight percent of the group receiving the drug treatment reported relief of symptoms, while 42% experienced side effects from the drug. Eighty-five percent of the group wearing sports bras reported relief of symptoms with no side effects (Hadi, 2000, pp 407-409).

Existing research on breast motion and desirability of specially designed sports bras confirmed the need for firm breast support, particularly among large breasted women (Boschma, et al, 1994; Eden, et al, 1992; Gehlsen & Albohm, 1980; Himmelsbach, et al, 1992; Lorentzen & Lawson, 1987; Mason et al, 1999). The consensus of these studies suggests that different cup size groups may require different support and design requirements and that the current industry practice of designing bras for various cup sizes in exactly the same way is unacceptable. This poses a real design challenge for the sports bra designer.

Ramifications from the inability to locate a good, supportive bra can manifest itself in the refusal to exercise, breast discomfort, and the irreversible breakdown of breast tissue. These problems are exacerbated for larger busted women. Large breasted teenage girls have indicated that they suffer from severe backache, are not able to participate in sports, and experience ridicule from classmates (Love, 2000).

Large breasts can be an impediment for a female athlete, especially in long distance running and in collision sports, such as soccer, ice hockey, etc (Haycock, 1978). Women who compete in sports such as these, as well as enjoy physically active lifestyles, require a good supportive bra. "Women already have a multitude of reasons for not participating in regular physical activity," said Sheryl Marks Brown, executive director for ACE (1998). "Breast discomfort doesn't have to be one of them."

Sports underwear has gained more visibility of late, both figuratively and literally. The sports bra has been alleged to be "as important to the growth of women's sports as the passage of Title IX" (Peck, 1999). "When Brandi Chastain scored the winning shot in a tense, overtime shootout with China in the World Cup soccer final, she did more than just shed her shirt to celebrate the team's triumph, she fired the hopes of sports bra makers everywhere" (Segal, 1999). In that moment of exuberance, Brandi revealed her black sports bra and brought instant attention and fame to a sturdy undergarment. The sports bra became "the cloth symbol of Title IX's success" (Gerhart, 1999). Annual bra sales reported January 14, 2002, indicated that sports bra sales comprised 6.1% of the $4.5 billion bra market (Dolbows, 2002).

There are two basic design styles of sports bras: compression and encapsulation. The former flattens breasts to redistribute their mass evenly across the chest; the latter supports each breast separately in its own cup. The design engineering of bras must defy laws of gravity and bras are often compared to suspension bridges with support coming from four directions: straps, band, circumference, and two intersecting 180° arcs of the cups (Nanas, 1964). To design a bra that accomplishes this engineering feat and is comfortable to wear requires a designer with expertise and a high level of heuristic knowledge, with heuristic knowledge being problem-solving techniques that use self-educating techniques (Hardaker & Fozzard, 1997).

In the past century, photographers used still cameras in the study of human and animal movement by taking a series of shots in an attempt to capture the movement to be studied. The type of movement and the analysis requirements largely determine the camera and analysis system of choice (Hall, 1991). Human motion analysis systems use marker sets, instrumented devices (such as electrogoniometers), and imaging methods ranging from television to video systems (Sampath, Abu-Faraj, Smith, & Harris, 1998).

Three-dimensional motion characterization can be obtained using cameras and optoelectronic techniques, which incorporate markers positioned on prominent anatomical landmarks of the subjects (Sampath, Abu-Faraj, Smith, & Harris, 1998). A quantitative film or video analysis is usually performed with computer-linked equipment that enables the calculation of movement. Digitizing is a traditional procedure for analyzing a film or video which involves the activation of a hand-held pen, cursor, or mouse over subject joint centers or other points of interest, with the x, y coordinates of each point subsequently stored in a computer data file (Hall, 1991).

Another approach to quantitative analysis of human movement eliminates the hand-digitizing process through the attachment of tiny electric lights known as light-emitting diodes (LEDs) or highly reflective markers over the body joint centers. Computer-linked cameras track these special lights or markers, enabling automatic calculation of the quantities of interest (Hall, 1991). In his endeavor to propose a soft-computing framework for human-machine system design, Zha describes another method to study the biomechanics of human motion developed by Peak Performance Technologies (2003). This system incorporates the use of passive reflective markers, along with a motion analyzer, a video recorder, video processor, and a desktop computer. Video data obtained from exercise sessions is digitized using this motion analysis system containing an analog-to-digital processor. In other words, the processor converts all reflections obtained from the passive reflective markers to digital outputs, which are further processed to determine postural coordinates and angles.

Purpose

This article compares breast support provided by a prototype sports bra with two commercially available sports bras. The prototype sports bra was designed to improve support using a combination of design features and selected materials.

Methods

Six physically active females between the ages of 23 and 37 (mean age 34 years) were recruited from local gyms offering aerobic exercise programs. To assure the accuracy of the self-reported breast size by each volunteer, the researcher took two different measurements: one under the breast (around the ribs) and one over the full breast circumference (over both bust points and around the rib cage). Each participating subject met the following breast size criteria: 32 DD, 34D/DD, or 36 C/D. With the passing of the physical screening, each participant was assumed capable of performing physical output and was asked to sign an informed consent form.

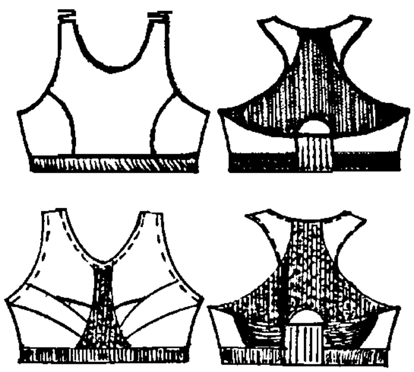
This study had one single independent variable defined as garment treatment that consisted of three levels: garment A (see Figure 1), the prototype sports bra with both compression and encapsulation characteristics; garment B (see Figure 2), a commercially available sports bra with compression and encapsulation characteristics, and garment C (see Figure 3), a commercially available compression sports bra. Starr and Krenzer (2000) developed the prototype sports bra using the functional design process delineated in Watkins (1995) incorporating, from the literature, characteristics that a good supportive bra sports bra should possess. A survey instrument, designed by the research team, determined users' perception of fit and performance of sports bras, users' design preferences, and insight into the complex engineering problem involved in designing performance sports bras. Design criteria and materials specifications were developed and ranked. The resulting prototype sports bra was designed to resolve specific comfort, support, and aesthetic issues reported by large breasted women through fabrication and design features. Bra fabrics were selected based on results from four textile laboratory tests, specifically: dimensional stability, pilling, abrasion resistance, and wicking tests (for more information see the Fabrication Table provided in Krenzer & Starr, in press). A 68% polyester/32% Lycra CoolMax® fabric with 2-way stretch, that performed better in dimensional stability and pilling tests than the other candidate fabrics, was used as the outer fabric. A brushed non-stretch, polyester and Hydrofil® nylon knit fabric with good wicking and dimensional stability results, was used for the interior fabric to form a stabilizing foundation.

The prototype combined an encapsulating inner bra with a compression styled outer bra in order to lift and support the breast tissue. It was hypothesized that the inner bra would help minimize breast displacement through its ability to separate and contain each individual breast. The straps were lined with non-stretch Hydrofil® nylon/polyester knit fabric to prevent stretching, a feature designed to increase support. Other features designed to reduce breast displacement included: racer-back styling for easy movement and wide, non-slip shoulder straps for better distribution of weight; 1½" band of elastic around the ribs for support and reduction of ride up; and adjustable shoulder straps and back band for improved fit and support.

Garment B combined an encapsulating inner bra with a compression style outer bra in order to lift and support the breast tissue (Figure 2). The inner bra was constructed of a non-stretch fabric of 56% cotton and 44% polyester and was advertised as having a hidden support panel that was purported to limit breast movement.

The outer fabric consisted of 43% cotton, 43% polyester, and 14% Lycra® spandex. An adjustable back closure and non-slip straps with Velcro® strips were additional features.

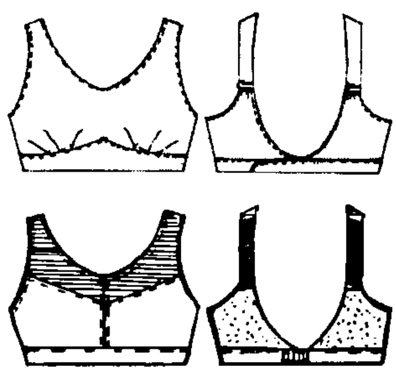
Garment C was a pull-on compression style sport bra constructed of 95% cotton and 5% Lycra® spandex (Figure 3). The racer-back styled sport bra was lined with 100% CoolMax® polyester and had 1?” wide straps.



Exterior Bra: **Front View:**
Shoulder Strap Adjustment,
1½” Wide Band
Back View
Mesh Insert: Single Layer,
Key-hole Opening,
1½” Wide Back Clasp

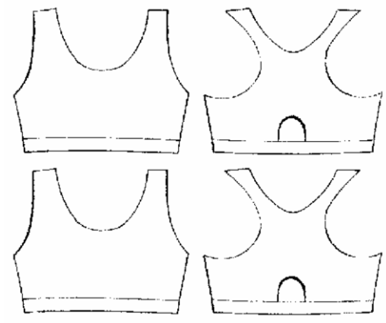
Inner Bra: **Front View**
Non-stretch seamed Cups,
Mesh Insert
Back View
Non-stretch Shoulder Straps,
Wings: Double layer of self-fabric

Figure 1. Garment Treatment A



Exterior Bra: **Front View:**
Band covered with self-fabric
Back View
Shoulder Strap Adjustment
13/8” Wide Back Clasp
Hook & Loop Tape Shoulder Strap
Inner Bra: **Front View**
Non-stretch Molded Cups
Front straps lined w/horizontal stretch fabric
Back View
Back straps lined w/lengthwise stretch fabric
Wings: Lycra® spandex-lined

Figure 2. Garment Treatment B



Exterior Bra: **Front View:**
1" Wide Band
Back View
Key-hole Opening

Inner Bra: **Fully-lined Front & Back**

Figure 3. Garment Treatment C

Physical characteristics that describe the style and unique design features of all three-garment treatments are included in Table 1. While design features were different for all three, each incorporated a support mechanism of some fashion. The foundation of both garment A and B's support system is the full inner support bra that encapsulated each breast individually, the only difference being that Garment A's inner bra was constructed of non-stretch fabric. Along with the inner support bra, garment A supported the breasts with an outer support bra that compressed the breast tissue to the chest cavity and non-stretch, racer-back style shoulder straps. Along with the inner support bra, garment B supported the breasts with an outer support bra that compressed the breast tissue to the chest cavity and stretchable, over-the-shoulder style bra straps. Garment C's support system relied on racer-back style shoulder straps and compression styling.

Table 1. Garment Style and Fit Features

	Garment A	Garment B	Garment C
Garment Style	Compression/ Encapsulation	Compression/Encapsulation	Compression
Moisture Management	CoolMax™ polyester/ spandex rib band, Exterior of 68% CoolMax™ polyester/32% spandex knit, Interior of polyester & Hydrofil® nylon knit, Back exterior mesh insert of 72% CoolMax™ polyester/28% spandex	CoolMax™ polyester/ spandex rib band, Exterior of 43% cotton/ 43% polyester/14% spandex knit, Interior of 56% cotton/ 44% CoolMax™ polyester knit	CoolMax™ polyester/ spandex rib band, Exterior of 95% cotton/ 5% spandex knit, Interior of CoolMax ™ polyester knit
Breast Movement Management	Full inner bra, non-stretch seamed cups, 1.625" non-stretch racer-back straps, 1.5" band, Pull-over compression due to fabric combination	Full inner bra, non-stretch molded cups, 1" stretchable shoulder straps, 1.375" band, Standard bra back opening style w/compression due to fabric combination	Stretch inner lining without cups, 1.125" stretchable, racer-back straps, 1" band, Pull-over compression due to fabric combination
Adjustability	4 hook back clasp, Shoulder straps with front adjustable plastic hook device	2 hook back clasp plus snaps, Back adjustable shoulder straps with hook and loop tape	No adjustability
Breathability	Fabrics noted above, Back key-hole opening, Back mesh insert, Front mesh insert between seamed cups	Fabrics noted above	Fabrics noted above, Back key-hole opening
Comfort	Cups and inner bra stitched with cover stitched seams, Plush-lined hardware, Wide, racer-back (non-slip) shoulder straps, Wide bra band, Inner bra – soft hand	Inner bra and molded cups stitched with French seams, Plush-lined hardware, Narrower shoulder straps, Wide bra band, Inner bra – soft hand	No seams to chafe, No hardware to chafe, Narrower racer-back (non-slip) shoulder straps, Narrower rib band, Inner lining – soft hand

Previous research projects videotaped subjects running on a treadmill in the nude (Haycock, Shierman, & Gillette, 1978; Lorentzen & Lawson, 1987; Lawson & Lorentzen, 1990; and Mason et al, 1999). According to researcher LaJean Lawson, high-speed film of the naked breast during running shows the breast stretches and distends considerably with each foot strike (Walzer, 1990, p 66). Earlier studies support the findings that the greatest relative displacements are in the vertical directions. Therefore, for purposes of this study, subjects were asked to engage in the same type, duration, and intensity of exercise, which would produce vertical body movement, for the testing of all three-garment treatments. As such, vertical breast displacement was the only dependent variable, for motion analysis, investigated in this study.

While running, the body moves up and down along with all appendages. To determine the amount of motion, for both the body and each breast, reflective markers were taped on the following anatomical landmarks: Lateral points of Acromion Processes, Sternal Angle, and both bust points. As the focus of this research was on breast support and breast displacement, the body's motion was subtracted from the overall breast motion to determine any excess breast displacement. Therefore, vertical breast displacement of the breast relative to the body during the first three running steps of each test session was calculated for each garment treatment.

A Repeated Measures Design with a Latin Square balancing scheme was used to minimize potential bias resulting from the order in which garments were tested, since the study also obtained perceptual data from the subjects. All six subjects wore each of the test garments in three separate test sessions. A tri-pod for the video camera and spotlight were set up directly in front of a treadmill, along the transverse axis and perpendicular to the frontal plane of each subject to record the breast displacement data from the best vantage point. The treadmill was positioned inside an environmental chamber draped in black felt to reduce glare. Breast displacement was recorded and analyzed, one frame at a time, during the first three running steps of each test session. Specified environmental chamber conditions were maintained at: 75º F ± 1º and 40% RH ± 5%, in order to obtain thermal comfort and physiological data of interest for a component not reported in this manuscript.

Upon arrival for the first test session at the Environmental Design Laboratory, each subject was given an introductory session to review the study protocol and all instruments. Reflective markers were shown to each subject, their placement demonstrated, the subject's role, and testing protocol was described. Once the review was completed, each subject stepped into the assigned changing area and donned their standardized clothing ensemble, along with the assigned garment treatment.

Each subject entered the chamber and stood at ease while being instrumented. Reflective circular markers were placed on anatomical landmarks using double-sided adhesive disks for subsequent digitizing and data analysis. Appropriate placement of reflective markers on the lateral points of the acromion processes and the sternal angle were identified by palpation of the respective bony prominences. Bust points were determined and marked by each subject, who then placed the reflective marker on the anatomical landmark. Once instrumentation was completed, subjects were asked to stand on the treadmill in the location that they would normally use for running. A spotlight was adjusted to shine directly on the markers for optimal reflection and to reduce glare in the subjects' eyes during videotaping. A super VHS video recorder was set up in the Environmental Design Laboratory and lined up directly with the sagittal plane of the subject.

Collection of vertical breast displacement began with the first running step of the exercise phase. Once the first three running strides were taped, the video recorder and the spotlight were turned off. Motion and data were collected and analyzed in inches, frame-by-frame, using a Peak Motus® Motion Measurement System. All instrumentation was removed at the conclusion of the test, and the subject was offered a sports drink and/or a bottle of water, after which, the subject and researcher left the environmental chamber. The subject changed back into her street clothes and confirmed the scheduling of the next session.

Discussion

The reflective markers placed on the sternal angle and both bust points identified body and breast reference points that provided data used to determine vertical breast displacement for each garment. It is important to realize that motion analysis is a step-by-step process. First, breast and body motion must be recorded to determine the high and low elevations (the rise and fall) of the body and breast during the exercise protocol.

Tracking one stride includes both a left and a right heel strike. Therefore, displacement was calculated for each leg on each stride. Three running strides were analyzed for this study yielding six measurements of displacement for each subject, breast, and leg. The total amount of vertical breast displacement for each subject and each garment was determined by finding the differences between the maximum and minimum vertical breast positions found over each of three running strides. Each individual's breast displacement was averaged to provide data by garment.

Figure 4 shows the average breast motion for each garment treatment, broken out by breast (right and left breast), stride (right and left leg), and repetition (1, 2, 3). There appears to be a trend for subjects wearing garment A to experience lower levels of breast displacement over the majority of the test, followed closely by subjects wearing garment B. Subjects wearing garment C appear to have experienced higher levels of vertical breast displacement over the majority of the test. As shown in Figure 4, the right and left step displacements are slightly different, as are the right and left breast displacement themselves.

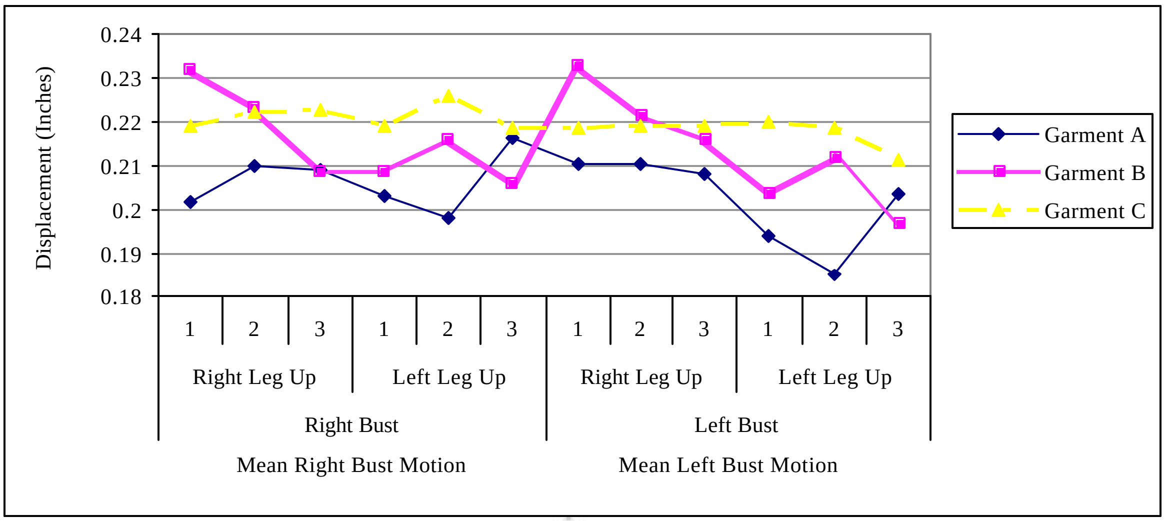


Figure 4. Average Bust Motion

Since it is not absolute breast motion that matters, but breast motion relative to trunk motion, it was necessary to calculate this difference. Trunk motion was calculated using the above process, repeated for the sternum. These values were subtracted from the breast displacement values to determine the relative breast displacement. The data show that subjects wearing garment C experienced greater breast displacement overall, as indicated in Figure 4. Subjects wearing garment C experienced a mean displacement of .045 inches, a 68% higher level of displacement than the .031 inches experienced by subjects wearing garments A and B.

ANOVA was used to determine significant differences for these data. ANOVA found a significant difference by subject, garment, and subject-by-garment interaction for relative breast displacement (see Table 2). The significant difference by subject (F= 55.47, p <.0001) was expected, because each person possesses not only a difference in breast mass for both breasts, but also a difference in age, number of children, skin tissue, ligaments, and levels of fitness. A significant difference by garment was predicted since garments A and B (both encapsulation and compression style sports bras) were designed to provide support for the breasts, and the data support this prediction. Table 3 shows the displacement interaction between garment treatments. There was no significant displacement difference between garments A and B.

Table 2. ANOVA: Biomechanical Displacement

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Subject***	5	0.02768554	0.00553711	55.47	<.0001
Leg	1	0.00007571	0.00007571	0.76	0.3851
Bust	1	0.00034561	0.00034561	3.46	0.0645
Garment***	2	0.00950675	0.00475337	47.62	<.0001
Subject-x-leg	5	0.00054168	0.00010834	1.09	0.3703
Subject-x-bust	5	0.00024265	0.00004853	0.49	0.7863
Subject-x-garment***	10	0.01544646	0.00154465	15.47	<.0001
Bust-x-garment	2	0.00003161	0.00001581	0.16	0.8537
Subject-bust-x-garment	10	0.00118221	0.00011822	1.18	0.3045
Error	172	0.01717050	0.00009983		

*$p \leq .05$. **$p = .001$. ***$p < .0001$.

Table 3. Tukey's Studentized Range (HSD): Displacement

Garment	Difference Between	Simultaneous	95% Confidence
Garment C-A***	0.013745	0.009780	0.017710
Garment C-B***	0.014210	0.010273	0.018147
Garment A-C***	-0.013745	-0.017710	-0.009780
Garment A-B	0.000465	-0.003500	0.004430
Garment B-C***	-0.014210	-0.018147	-0.010273
Garment B-A	-0.000465	-0.004430	0.003500

Comparisons significant at the 0.05 level are indicated by ***

Multiple regression, a statistical analysis using categorical predictors with orthogonal coding and orthogonal contrasting scheme, was run on the breast motion data. From this analysis, it was determined that approximately 13% of the variability in breast displacement was predicted by garment treatment. In other words, garment treatment accounted for approximately 13% of the total variance in breast movement. Garment treatment was statistically significant for breast displacement [F (2, 213) = 16.393; p< .0001)], see Tables 4 and 5.

Table 4. Categorical Predictors Model Summary (Orthogonal Coding & Orthogonal Contrasting Scheme)

Mode	R	R	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square	F Change	df1	df2	Sig. F
Change				Change					
1	.365[a] .00001	.133	.125	.017508	.133	16.393	2	213	

a Predictors: (Constant), x2grmtabvsc, xlgrmtavsb

d Dependent Variable: x6 displacement score

Table 5. Descriptive Statistics

	Mean	Std. Deviation	N
x6 displ score	.035701	.0187201	216
x1grmtavsb	.00	.818	216
x2grmtabvsc	.00	1.417	216

Conclusions, Implications, and Recommendations for Future Studies

Garments A and B are similar in that they both include encapsulation and compression styling, whereas, garment C is solely compression styling. The three bras also differ in choice of fabric, closure methods, and strap and cup styling. Thus, differences in support and comfort between the three garments were anticipated to be due to design features and/or fabric combinations. Seam choices were designed to reduce the potential of chafing and skin irritation. The interior bra of garments A and B were stitched with a cover stitch and French seams respectively. In addition, both garments A and B had plush-lined hardware. The racer-back shoulder straps of garments A and C were designed to provide comfort and a non-slip advantage over the standard shoulder strap style featured in garment B. Garment A features an inner bra of soft, brushed Hydrofil® nylon and polyester knit, wide shoulder straps, and a wide rib band for additional comfort. Garments A and B provided sizing adjustability through the incorporation of adjustable back closures and straps. Garment C provided adjustability via the stretch fabric only. A second component of the original study addressed thermal comfort and moisture management issues (Starr, 2002).

Figure 4 indicates a trend for subjects wearing garment C to experience the highest breast motion and subjects wearing garment A to experience the lowest breast motion. Subjects wearing garment C experienced the highest amount of relative breast displacement with a mean of .045, but the differences of relative breast displacement between subjects wearing garments A (prototype) and B are small. ANOVA found a significant difference for subject, garment, and the subject-by-garment interaction for relative breast displacement. There were significant differences between garments A (prototype) and C, as well as between garments B and C. There was no significant difference between garments A (prototype) and B. Subject-by-garment differences were expected, due to individual differences and the differences in fabric/garment characteristics.

Several key differences between the three garments could have influenced the results of the displacement data. The inner bra and wide straps of garment A were constructed using non-stretch materials and garments B and C used stretch materials. Secondly, the width of the straps and bands could have influenced bra support. Garment A had wider shoulder straps than garments B and C. Garments A and B had wider bands than garment C. Thirdly, garments A and B provided encapsulation plus compression styling as compared with garment C that provided compression only.

Lorentzen and Lawson found that bras that scored highest in perceived support had the following design features and materials: high modulus knit fabrics with low extensibility, straps stabilized with non-elastic materials to allow minimal stretch, and a bra style that compressed the breasts against the chest wall (1990). These results influenced the design of prototype A's inner bra and wide racer-back shoulder strap system. In contrast, garment B used stretch materials for an inner bra and narrower shoulder straps. Both used a wide rib band and a combination of compression and encapsulation styling. Thus, the use of stretch versus non-stretch materials and width of the shoulder straps were major differences in these two bras that could have influenced breast support. The finding of no significant difference in relative breast displacement between the two bras suggests that the use of stretch versus non-stretch materials is inconclusive as a mechanism to provide breast support. In contrast, garment C, which used stretch materials, narrower straps and bra band, and compression styling, provided significantly higher relative breast displacement data. Recognizing that the features of all three bras were not systematically controlled to be able to definitively indicate which feature influenced support the most, nevertheless, the data suggest that two design features, band width, and style type, appear to be the most influential features in providing breast support. Therefore, physically active women who are large-busted should wear sports bras that have both compression and encapsulation styling and wide bands for greater support.

Fit was varied among the subject pool even with considerable care in pre-screening to ensure a similar size-range and breast mass. Locating large-busted women who regularly jog or run for any length of time was difficult, therefore the size criteria was lowered somewhat. All participants wore size D or DD, but were smaller around the rib cage and wore a smaller band size than expected. Since bra band size is related to cup size, both must be considered when determining total breast mass. There were extremes of life styles and experiences represented within this group of women, who ranged between the ages of 22 and 37 years. Data may have varied due to these individual differences.

The results of this study support the findings of previous research studies regarding the need for firm breast support, particularly for large-breasted women (Boschma, et al, 1994; Eden, et al, 1992; Gehlsen & Albohm, 1980; Haycock, Shierman, & Gillette, 1978; Himmelsbach, et al, 1992; Lawson & Lorentzen, 1990; Lorentzen & Lawson, 1987; Mason et al, 1999). If, as these studies suggest, larger-busted women require different support and design systems, the current industry practice of producing bras in all sizes with the same design features and fabrications should be re-examined. Additional recommendations for further research include conducting: 1) a similar investigation with a larger subject population with breast size and body type systematically varied, 2) field studies with athletes participating in selected sports, 3) a similar investigation with one garment design and fabrication systematically varied, and 5) a study that tests the possible need for different bra materials and designs for different body types.

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