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Original Research

An Experimental Comparative Study on the Commercial Sports bras Combined with an Electromechanical Modeling

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ABSTRACT

One of the main points when exercising is the use of proper sportswear to minimize injuries and improve athlete performance. This study aimed to investigate the effects of the design, the number of components and seams, and the presence of pads on the movement comfort of sports bras. Two popular sports bras were considered: one containing some components and sewn seam and the other is a seamless bra without pads. To measure the bra tension during sports activity, a metal thread sensor was implemented for recording motion changes. To simulate the simple movements of sports activities, three movements of the hand and body were performed. The stretch changes of the bra were recorded in the form of voltage changes. The results showed that the seamless sports bra in the shoulder straps put more stress on the body; however, this sample in the bottom of the gore and the bottom of the wing-back had fewer voltage changes than those of the other type. The racing back bra offers better support than other types due to its special design and covering more areas of the athlete's back with elastic fabric. The Increased number of bra components and seams and the presence of pads increase tension, resulting in reduced comfort at the gore and the bottom of the wing-back. An equivalent electromechanical model presented in the research for theoretical modeling of the sensor behavior, also confirms the experimental results and shows a high correlation coefficient (75% and more) between the experimental results and the model.

Keywords: Commercial sports bra, Breast movement, Movement comfort, Metal yarn sensor, Electromechanical model

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INTRODUCTION

In recent years, raising public awareness of the need for a healthy life, exercise and fitness have received more attention than previously (1). One of the main areas is choosing the right sportswear to minimize injuries and maximize the quality of activity performance with ideal protection and comfort. Sports bras are a type of women's clothing that is especially important because they stick directly to the breast. Pressure on the nerves under the skin of the breast can cause discomfort, pain, reduced tolerance, and rapid malaise (2). During light to heavy sports activities, breast movement and displacement increase compared to resting activities (3). In addition, the breasts move in all directions, which high displacement causes injury to the structure of the breasts and affects the health of the breasts and the individual. Especially if the exercise is repeated continuously without controlling excessive breasts displacement, this will lead to irreversible injuries (4).

Therefore, it is crucial to use suitable sports bras that provide women health by restricting breasts movement and preventing injury to their tissue, and also improving comfort and performance, cause to enjoy more in sports and exercises (3, 5). Sports bras should be different from regular bras (6) and provide two things more: compression and independence. Compression means that the sports bra is designed to press the breasts against the chest as much as possible and prevent them from moving freely during exercise. Independence also means that sports bras control the movements of each breast freely and independently of the other, and this feature allows them to provide the best support for the movement of each breast separately during exercise in any situation (5, 7).

Many women use sports bras to reduce the pain and discomfort caused by breast movements during exercise. Some sports bras are even designed to be worn when doing heavy exercise such as running (8). The support level of a sports bra that should prevent the breasts from moving around, is one of the main factors in choosing it. The higher the level of support, the tighter the sports bra will be (6, 9). Therefore, the more active exercises, the higher the support level needed. Due to a wide range of breast mass volume and biomechanical considerations, the size of the bra force in the standing position and during physical activity, especially in the downward stage of the breast movement cycle, is essential in designing the best sports bra (10). Although the main feature of the sports bra is to limit the movement of the breasts, a sports bra should allow athletes to perform a comfortable exercise in addition to restricting breasts movement and related pain (9). It is clear that the pressure on the body from the sports bra, which is required to support the breasts, is one of the negative factors related to clothing comfort, especially in movement comfort. On the other hand, the fit of the sports bra is essential for bearing the weight of the breasts and its optimal protection (11).

The design of the bra should be such as to prevent the pressure concentration on the sensitive areas and distribute the tension in the less delicate areas of the body (2). Previous researches have reported that most of the pressure is on the upper shoulder and under the elastic band on the front and back of the bra, and tight underwear can lead to negative physiological effects such as neck and shoulder pain (12, 2). The degree of fabric elasticity and the different patterns design are two important factors in the production of the desired bra in terms of compression and movement; In such a way that the tightness of the underwear is such that the person in both resting and moving positions, feels support and movement comfort without undesirable pressure (13). According to the structure of the sports bra in Figure 1, to achieve the desired support and comfort, the sports bra components need to be adjusted to tension, changing design factors such as the pattern and number of bra components. And stress needs to be reduced (12).

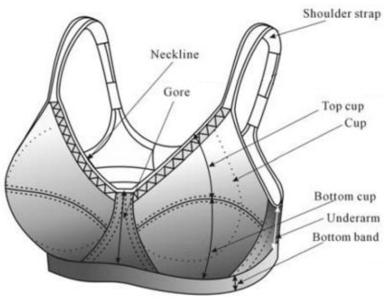

Figure 1. Anatomy of a sports bra (14)

The first sports bra was made in 1975 by sewing two jacks together, providing more support to the breasts during exercise compared to regular bras (15, 16). From the past till now, it has been always tried to improve the support level and comfort of the sports bra by using its proper design. Most studies have investigated the effect of sports bras on the kinematic limitations of the breast (17-20), its pressure on the breasts (21), and the resulting breast pain (22, 23-25). Researchers have also evaluated breast motion and the effect of a sports bra on light exercises such as walking and heavy exercise such as running, treadmill running, one-step jumping, and two-step jumping (23, 25-28).

Research into sports bra design has increased exponentially in recent years (29). Researchers at the University of Portsmouth have studied how the breast moves and how much it is injured during exercise from a biomechanical, physiological, and clinical perspective. The results showed that 72% of female athletes had chest pain during physical activity. The anatomy of the breast contains only a natural support structure called Cooper's ligament. This is the fibrous connection between the inside of the breast skin and the pectoral muscles. They found that this structure was more flexible (about 2 centimeters) than usual during exercise. Therefore, the soft tissues in the breast are damaged by tension, leading to long-term sagging and loss of shape. Their study showed that the use of sports bras significantly reduced damage to the soft tissues of the breast. In addition, women who wear proper sports bras while exercising are more confident and interested than women who use regular bras or who do not wear bras at all (4).

Sports bra design is a special process that requires a combination of creativity, design, accurate patterning skills, and a good understanding of fabric characteristics (30). Sports bra design includes initial design and fabric selection, patterning, grading, and evaluative wearing testing. In the design and manufacture of sports bras, the criteria or model for measuring and modeling the breast must first be determined. The obesity index and waist circumference are currently used to assess obesity. The Body Volume Index is a completely new and reproducible concept with a 3D body scanner and corresponding software for measuring the volume of eight body segments such as the abdomen and breasts (31). There are many important parameters to consider when choosing the right sports bra such as the value of protection and support depending on the intensity, comfort, sewing, color, shape, beauty, and more of the sporting activity (5-7).

Wearable electrical sensors developed over the past decade have led to some new technological advances in designing smart, small, and lightweight monitoring systems (32, 33). The purpose of this study is to investigate the effect of sports bra design on movement comfort by comparing two commercial sports bras to improve performance and promote the health of female athletes. The movement changes are measured in a new way by sewing a metal thread onto the sports bra as a sensor during exercise. An electromechanical model was also developed and proposed to verify the response of the sensor.

MATERIAL AND METHODS

In this study, to investigate the effect of bra design on movement comfort during activities and training, two types of commercial sports bras were used: 1) non-padded seamless sports bra that had only a seam on top of the shoulders (sample SB1), 2) spongy sports bra with several components (sample SB2). These two samples are shown in Figure 2.

To evaluate the movement comfort of sports bras, a new measurement method was used. In this way, the tensile changes caused by the movement of the athlete's hand are recorded and examined using a sensor stitched to the garment. A conductive metal thread of Ne 20 containing 28% steel and 80% polyester was used as a force sensor. Based on previous studies (34, 35) and to evaluate the effect of design on the comfort of the bra, the three areas with the most tension were selected for stitching the sensor (metal thread): shoulder strap, under the gore, and the bottom of the wing-back (back band). The metal thread in these three parts of the sports bra was sewn manually and symmetrically at a distance of 10 cm, and 8-10 cm of the extra thread was held from the two ends to connect to the test electrical circuit. To increase the accuracy of the test, this stitching was done in three rows at intervals of 3 mm in the tension-less state and with the stitching density of 1 stitch/cm. A sensor-stitched sample is shown in Figure 3.

Figure 2. Samples prepared to evaluate movement comfort: a) non-padded seamless sports bra that had only a seam on top of the shoulders (sample SB1), b) spongy sports bra with some components (sample SB2)

Figure 3. Selected areas for sewing metal thread to a sports bra

After preparation, the samples of sports bras were worn by a 22-year-old woman with a size of 38 and a body mass index of 20. Then the alligator clips were attached to the two ends of the conductive threads stitched to the clothes to create the electrical circuit. Then the movement of the hand and body was performed according to simulate the simple movements of sports activities: a) two hands are pulled upwards, b) both hands are pulled backward, c) both hands are opened around and rotated from the arm (Figure 4). The relevant software also started recording the produced model with each movement. This experiment was repeated in each movement for 2 similar samples of each garment and the voltage-time diagrams were recorded.

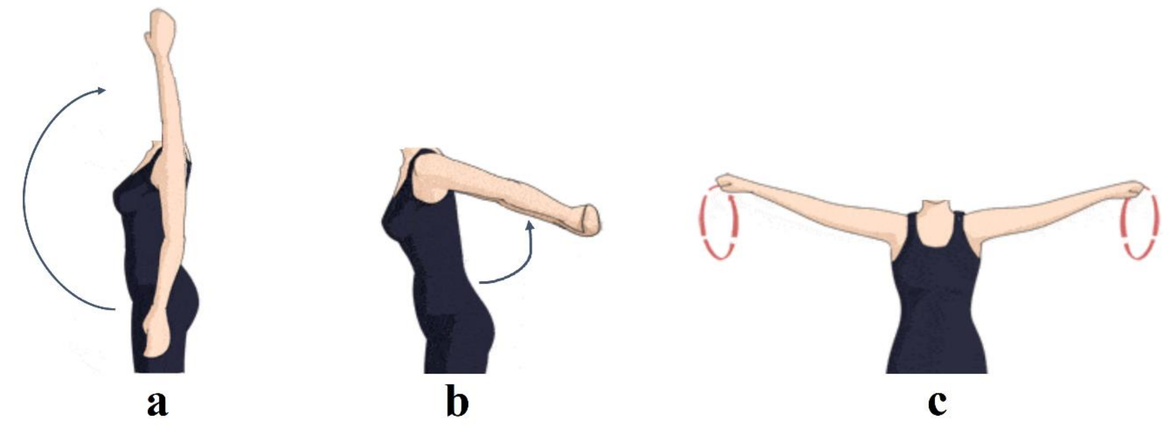

Figure 4. Hand motions to evaluate the movement comfort of the sports bras: a) two hands are pulled upwards (Exercise 1), b) both hands are pulled backward (Exercise 2), c) both hands are opened around and rotated from the arm (Exercise 3)

An electrical circuit including a computer, a sensor, alligator clips, a circuit board, and a power supply was used to record the test data. The analog quantity of the yarn length variation was translated into the numerical quantity of resistance using an Analog-to-Digital converter. The electric board was connected to the two ends of 3 rows of the metal yarns with a long connection to investigate the output voltage variations during the metal yarn elongation; also, its specific resistance was measured. Afterward, the samples worn by the individual were applied to the circuit to record the voltage variations during the metal yarn elongation through performing different movements (Figure 5). It was possible to convert the recorded voltage variations for each sample into resistance variations (36), which will be further explained by introducing the theoretical model governing this measurement method. The resistance variations were transferred to the computer connected to the board by a device. Figure 6 illustrates the structure of the electronic circuit.

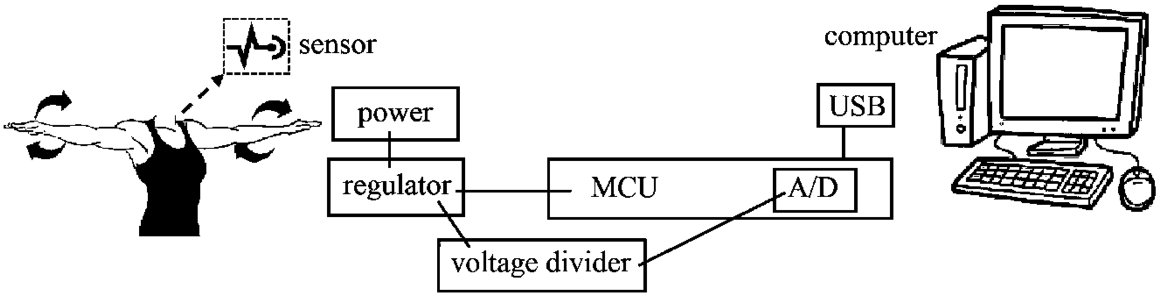

Figure 5. Electronic circuit components recording the tension variations

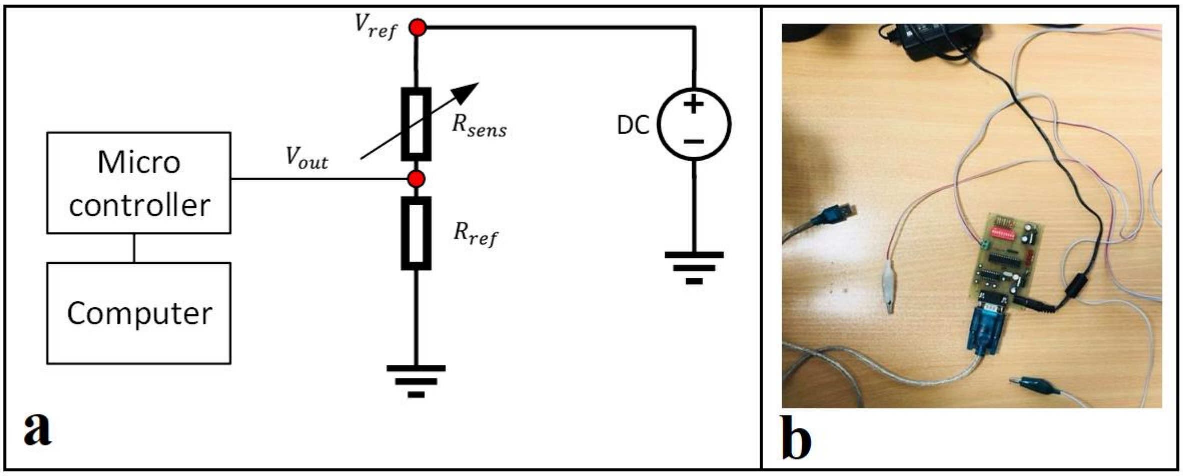

Figure 6. a) Electrical model for recording tension variation, b) Electrical equipment used in the experiment (24)

It is crucial to evaluate the movement comfort qualitatively. To this, the movement comfort of each sample was evaluated during the wearing trial by the individual. In such a way that after wearing each sample and performing the usual movements, the subject completed a comfort evaluation questionnaire which contained a question and was scored as very unpleasant, unpleasant, moderate, comfortable, and very comfortable.

Development of an equivalent electromechanical model for theoretical modeling of the sensor behavior

A method of measuring the tension variation of clothing using metal thread as a force sensor has been used in several studies. In this research, an attempt has been made to use the longitudinal changes of metal thread to create a theoretical model. For this purpose and considering the study of force changes in small strain, the elasticity of the sensor (metal thread containing 28% steel) has been used in the elastic area. The diameter and length of the wire change with changing the force applied to this wire. This change in the length and diameter of the wire leads to a change in electrical resistance of the wire resulting in the change of the voltage accordingly. Therefore, the instantaneous voltage changes are proportional to the force applied to the steel wire. The electrical model equivalent to the performed experiment is shown in Fig. 6a. In this model, the stretched wire is displayed as a variable resistor with time, R_{sens} (t). This variable resistor is in series with a constant resistor, R_{ref}, and as shown in Equation 1, V_{out} (t) can be calculated by the resistive divider relation.

$$V_{out}(t) = \frac{R_2}{R_1(t)+R_2} V_1 \qquad (1)$$

To extract R_{sens} (t), it is necessary to calculate the change in length and cross-sectional area of the steel wire due to the applied tensile force. As shown in Figure 7, the force (F) applied to both ends of the wire causes to change the length of the wire (ΔL). Assuming the wire is in the elastic area, the relationship between the length change and the force applied to both ends of the wires is expressed in Equation 2. In this relation derived from Hooke's law, Y is Young's modulus (which for the steel material used in this experiment is 210 * 10 ^ 9 N⁄m ^ 2), A is the wire cross-section, and L_0 is the initial length of the wire.

$$\Delta L = \frac{1}{Y} \frac{F}{A} L_0 \qquad (2)$$

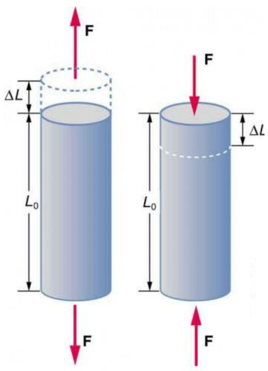

Figure 7. Elastic model of the force applied to the steel wire

By changing the length of the wire and assuming that the volume of the wire is constant before and after elongation, Equation 3 is extracted.

$A_0 L_0 = A_1 L_1,\ r_0^2 L_0 = r_1^2 (L_0 + \Delta L)$ (3)

By placing equation 2 in equation 3 and simplifying, the new radius and length of the wire are extracted by the applied tensile force, which is expressed in equations 4 and 5.

$L_1 = (1 + \frac{1}{Y}\frac{F}{A}) L_0$ (4)

$r_1 = \frac{1}{\sqrt{(1+\frac{1}{Y}\frac{F}{A})}} r_0$ (5)

By changing the length and diameter of the wire, its electrical resistance also changes. Equation 6 expresses the electrical resistance of the wire. In this relation, ρ is the specific electrical conductivity of the material, which is 76 * 10 ^ (-8) Ω.m for steel.

$R = \rho\ \frac{l}{A}$ (6)

By inserting relations 4 and 5 in relation 6, the relationship between the electrical resistance of the wire and the force applied to it is calculated and expressed in relation 7.

$R(t) = \frac{\rho}{\pi}\ (1 + \frac{1}{Y}\ \frac{F(t)}{A})^2\ \frac{L_0}{r_0^2}$ (7)

Then, by inserting Equation 7 in Equation 1, the relationship between the force applied to the steel wire and the measured voltage is extracted and expressed in Equation 8.

$V_{out}(t) = \frac{R_{ref}}{\frac{\rho}{\pi}(1+\frac{1}{Y}\frac{F(t)}{A})^2 \frac{L_0}{r_0^2} + R_{ref}} V_{ref}$ (8)

As can be seen, the measured voltage is inversely proportional to the square of the applied force, and the final relationship is extracted by entering the specific conductivity values, Young's modulus, the parameters of the length and initial radius of the wire, as well as the constant resistance and voltage of the power supply. Therefore, the force input from the following formula can be estimated using the measured voltage. In this study, the values of R_{ref} and V_{ref} are 8 Ohms and 5 Volts, respectively. The initial radius of the metal thread is also extracted using its count (59.5 tex). By placing values, the values of force at each voltage can be calculated.

RESULTS

For each sample of the sports bra, according to three sewing positions of metal thread, three separate movements, and two repetitions of the experiment, 18 diagrams of voltage changes over time were obtained. To more accurately express and compare the results, the slope of the voltage-time diagram has been used as a measure of voltage changes during movement or in other words, changes in elongation in the bra. The average of the test results for each sample is shown in Figure 8. Also, the T-test result for equality of means is reported in Table 1.

Table 1. T-test results for equality of means

positions of the sensor stitched	**Exercise**	**Variables**	**t**	**Sig.(2-tailed)**	**95% Confidence Interval of the Difference**	
					Lower	**Upper**
The shoulder strap	1	SB1, SB2	9.563	0.163	-0.007359	0.004104
	2	SB1, SB2	-2.236	0.155	-0.002581	0.000563
	3	SB1, SB2	6.574	0.022	0.000948	0.005119
The bottom of the gore	1	SB1, SB2	-13.282	0.069	-0.005331	0.003969
	2	SB1, SB2	0.894	0.465	-0.000681	0.001319
	3	SB1, SB2	40.305	0.001	0.004839	0.006421
The bottom of the wing-back	1	SB1, SB2	2.121	0.168	-0.000319	0.000781
	2	SB1, SB2	0.181	0.886	-0.019814	0.016193
	3	SB1, SB2	-4.032	0.048	0.000269	0.001562

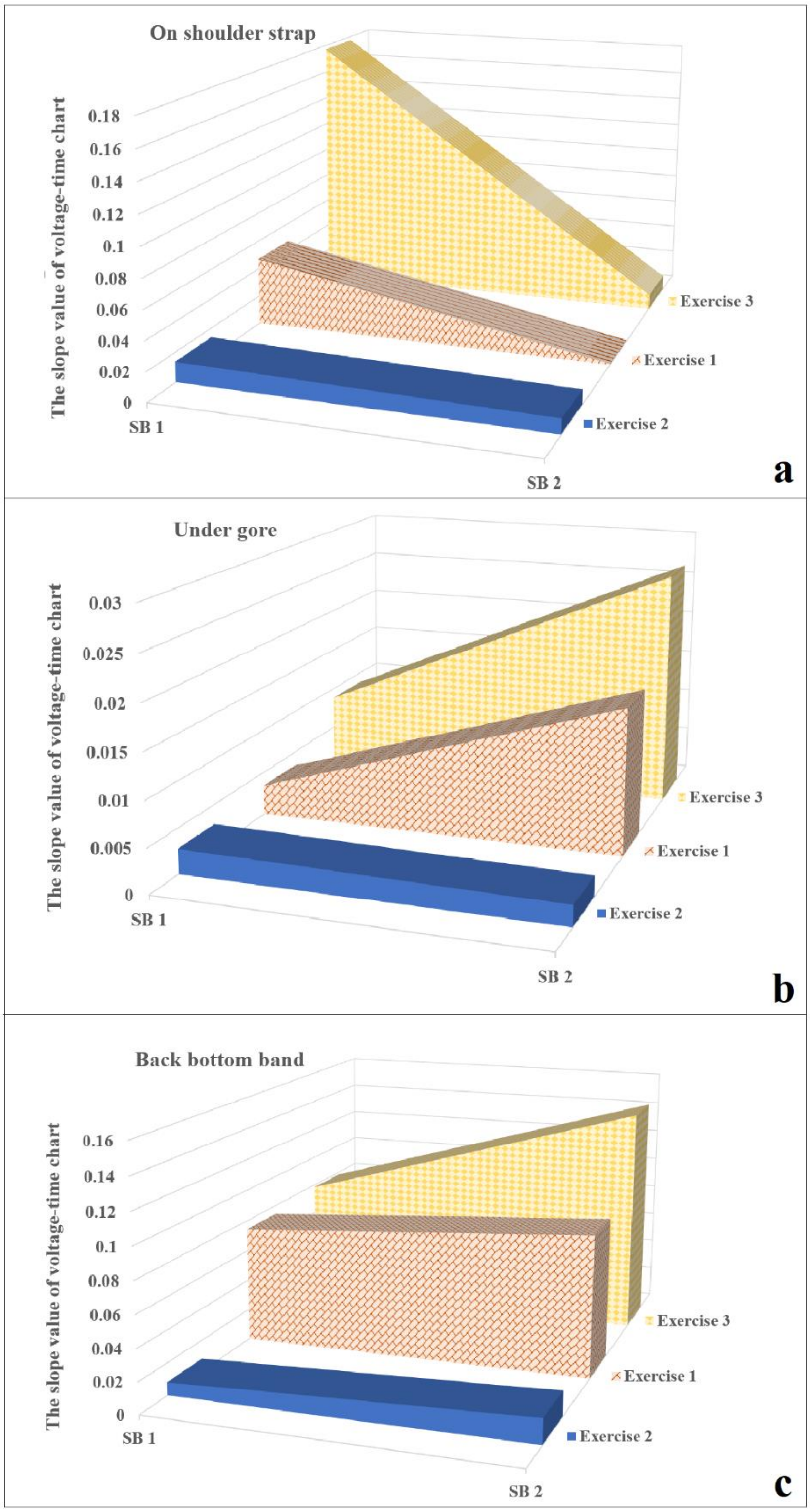

Figure 8. The value of the slope of the voltage-time diagram during exercise for three positions of the sensor stitched at a) the shoulder strap, b) the bottom of the gore, (c) the bottom of the wing-back (back band)

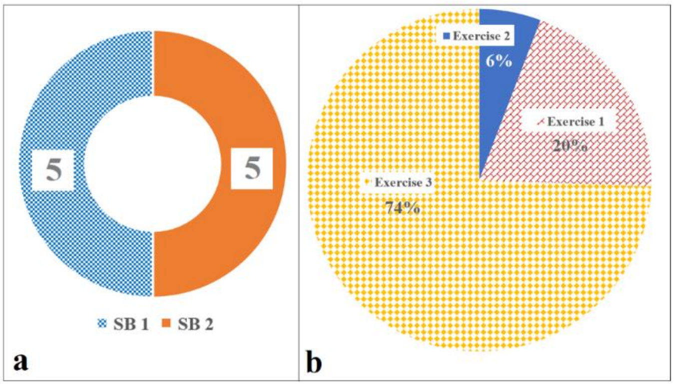

Figure 9. a) Quality evaluation results of sports bra samples (graded from 1 very unpleasant to 5 very good), b) pie chart of the results

A schematical graphic of all the results of this study is shown in Figure 9b. As can be seen in this figure, in both sports bras and all three positions of the sensor, the voltage changes during exercise 3 that mean opening the two arms around and rotating the arm, are the largest amount in comparison to two other motions. Exercise 2 which means both hands are pulled backward causes to create the lowest amount of voltage changes. Also, only during exercise 3, a significant difference is between the two samples SB1 and SB2 (P-values are 0.022, 0.001 and, 0.048).

Developed electromechanical model

By introducing the test values to the presented electromechanical model, the force values were calculated using the voltage. The experimental voltage values obtained from the test as well as the estimated force of the model are shown in Figure 10. In this figure, the inverse relationship between voltage and estimated force with a high correlation coefficient (above 75%) can be seen. Although this model was developed using simple assumptions, its calculation of the sensor force can be a good criterion for comparing the elongation created in clothing during sports activity and also for movement comfort.

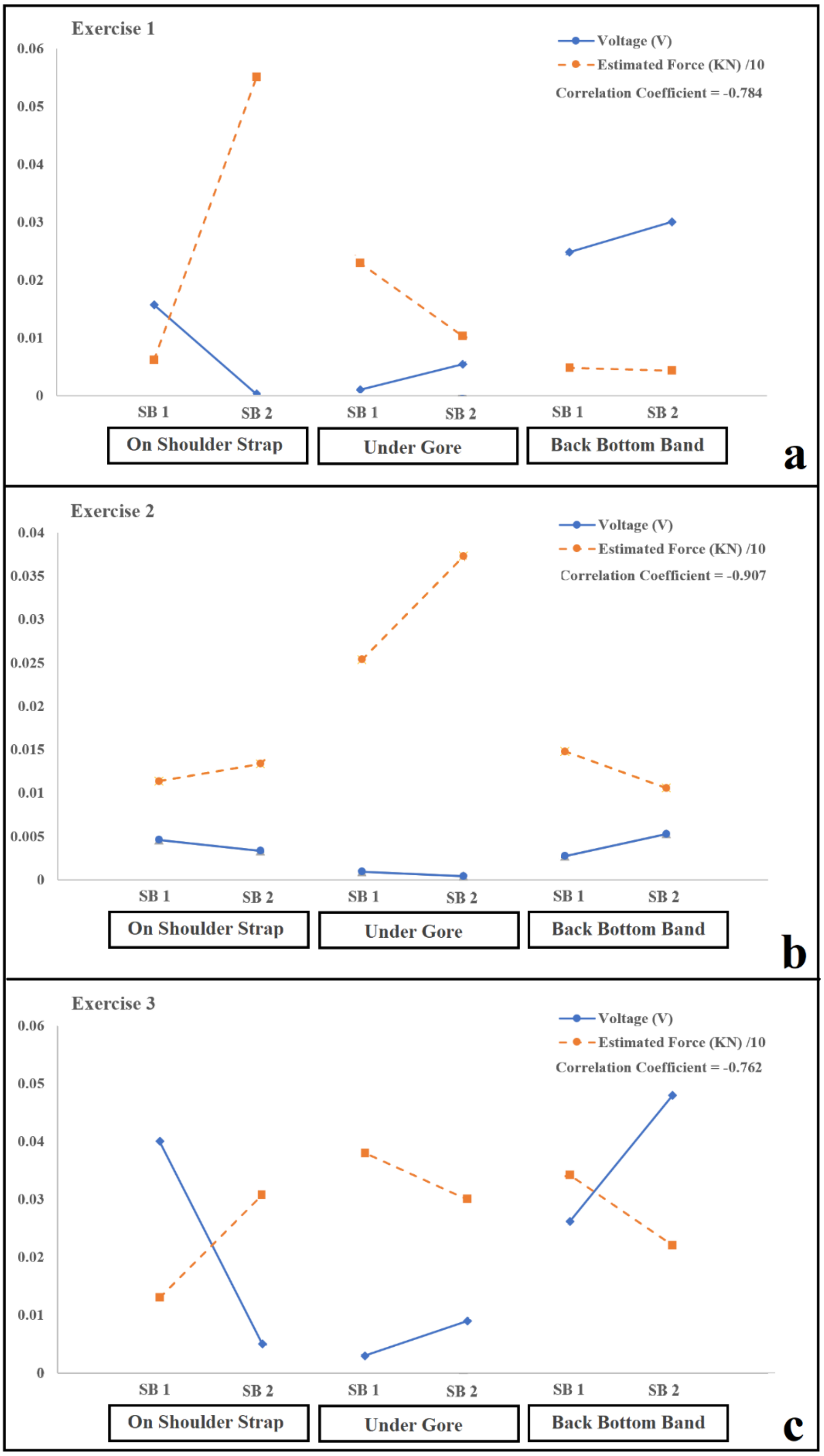

Figure 10. Estimated values of voltage and force of the model in three areas of the sensor during: a) Exercise 1, b) Exercise 2, (c) Exercise 3

DISCUSSION

The voltage changes of the metal thread sewn to the underwear are a criterion of its tension changes during hand and body movements during sports activities. By applying the movement force resulting from sports activities, the bra becomes elongated and deformed. Increasing the length of the bra leads to longitudinal changes in the stitched conductive thread sensor resulting in a change in the voltage of the electrical circuit by changing the resistance of the conductive thread. Based on the voltage changes, the stress on the bra in the area of the metal thread sensor can be quantitatively evaluated and compared.

Comparison of the slope values of the voltage-time diagram for different samples shows that in all the simple sports motions performed in this study, the seamless bra (SB1) in the shoulder strap position puts more stress on the body (Figure 6a). Although this sample in the low positions of the gore and the wing-back (back band) have fewer values of voltage changes than the sample containing some components and sewn seam, the results of the qualitative evaluation (Figure 9a) show the same satisfaction of the participant with both samples. The SB2 is the racing back bra that provides better support than the other type. Because of the Y-shaped shape straps, the particular design of SB2 allows more areas of the athlete's back to be covered by the elastic fabric of the bra, resulting in better support. It seems that more support of the bra in the shoulder strap reduces tension, and thus it is expected the ease movement in the shoulder area. Therefore, the wider the straps used in the sports bra, the better the bra can provide support, and usually, the wider straps are more comfortable than thinner straps, and they have a longer life span with retaining their elasticity and shape.

A comparison of the results related to the bottom of the gore and the of the wing-back (back band) (Figure 8. B and C) indicates that in all exercises performed in this study, the slope of the voltage-time diagram in the SB1 sample is lower than that in the SB2 sample. In other words, the seamless bra without pads has fewer voltage changes during three sports movements at the bottom of the gore and the of the wing-back (back band). Increasing the number of bra components and sewn seams in addition to the presence of pads can increase the tension and result in less movement comfort for the athlete than the SB1 sample.

A good sports bra should prevent the free movement of the breast in all directions and its excessive motion during exercise so that the freedom of action during exercise increases and the athlete focuses on doing sports movements instead of breast movements! As mentioned previously, regular, non-padded bras designed for daily use provide more freedom of movement for the breasts than sports bras. Therefore, because the breast may be more mobile, this type of bra can cause pain, rupture of the breast tissue due to sudden movements of exercise, and even a change in the shape of the breast in the long run. With the use of a proper exercise bra, exercise-induced injuries to the soft tissues of the breast are considerably decreased, and exercise becomes lighter and more attractive for women (4-7). Adding bra components and sewn seams, increasing shoulder width, increasing the area covered by the bra, and using pads increase the support of the bra from the breast during sports movements and reduce sports injuries, but the higher the level of support, the tighter the sports bra will be. It holds the breasts more firmly in motion, which results in increasing the tension and decreasing the athlete's comfort compared to the non-padded seamless bra. For this reason, it is recommended to use suitable sports bras to participate in different sports at various levels. The best sports bra for any exercise activity should be able to minimize excessive movement of the breasts in that activity and has good support and maintenance. For example, seamless sports bras, without pads and with simple straps that have little support, are suitable for light exercise, walking, and yoga, and are even used daily, while their use for heavy exercise like running, climbing, and getting fitness, breast tissue significantly increases the risk of breast injury.

As shown in Figure 10, the SB2 specimen in the shoulder strap shows a higher value of the force than the SB1 specimen and consequently has a higher elongation (according to Equation 2, the elongation is directly related to the force). On the other hand, its voltage changes are low. Previously, statistical results have shown that the SB2 model, due to its design in the shoulder area, has better support with increased elasticity and reduces tension, and consequently, provides greater movement comfort in the shoulder area. Also, the model results confirm that this sample in the shoulder area has higher elongation and results in bringing more comfort to the athlete. Other values of force estimated by the model also confirm the analysis of statistical results.

CONCLUSION

Sports bras are one of the most important and widely used sportswear for women. the correct design of the sports bra for increased comfort of movement plays a very important role in optimally controlling breast movements during sports activities. In this study, the effects of various sports bra designs that reduce tension and improve comfort movement during three simple sports exercises have been investigated using a new method based on the use of sewn metal thread sensors to detect movement changes during sports activities. The results showed that for all the simple sports movements performed in this study, the non-padded seamless sports bra in the shoulder strap puts more stress on the body, but this sample shows fewer values of voltage changes in the bottom of the gore and the bottom of the wing-back (back band). Due to its special design, the racing back bra has better hold than other types. Bra proportions and seams, shoulder width, bra-covered areas, and padding provide better bra support to the breast and reduce the risk of injury during sporting activities. The results show that the change in tension when opening the two arms and rotating the arms is maximal compared to the other two movements. An Electromechanical model was also developed to model sensor behavior based on theoretical relationships, and experimental results were successfully validated with high correlation.

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مطالعه‌ی مقایسه‌ای تجربی بر روی نیم‌تنه‌های ورزشی تجاری همراه با مدل سازی الکترومکانیکی

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یکی از مهمترین نکات هنگام ورزش کردن استفاده از لباس ورزشی مناسب برای به حداقل رساندن آسیب ها و بهبود عملکرد ورزشکاران است. هدف این تحقیق بررسی تأثیر طراحی، تعداد برش و درز و وجود کاپ در نیم‌تنه‌ی ورزشی بر راحتی حرکتی ورزشکار است. **روش کار:** دو نوع نیم‌تنه‌ی ورزشی تجاری شامل مدل دارای برش و درز و همچنین دارای پد، و مدل بدون درز و بدون پد در نظر گرفته شد. جهت اندازه‌گیری معیاری از تنش و همچنین راحتی حرکتی نیم‌تنه، از نخ فلزی به عنوان حسگر ثبت تغییرات حرکتی استفاده شد. با استفاده از یک مدل الکترومکانیکی، تغییرات کششی نیم‌تنه ناشی از حرکات بدن در حین فعالیت‌های ورزشی در سه قسمت بند شانه، پایین نوار پشتی و پایین سه‌گوش میانی توسط سنسور نخ فلزی به‌صورت تغییرات ولتاژ ثبت شد و معیار بررسی راحتی حرکتی لباس زیر قرار گرفت. **نتایج و بحث:** در تمامی حرکات ساده‌ی ورزشی انجام شده، نیم‌تنه‌ی بدون درز و پد در موقعیت بند شانه تنش بیشتری به بدن وارد می‌آورد، هر چند این نمونه در دو موقعیت پایین سه‌گوش میانی و پایین نوار پشتی مقادیر کمتری از تغییرات ولتاژ نسبت به نمونه‌ی دارای درز و پد دارد. نمونه‌ی دارای بندهای شانه‌ی مسابقه ای به دلیل طراحی خاص و پوشانیدن نواحی بیشتری از پشت ورزشکار توسط پارچه‌ی کشسان، پشتیبانی بهتری نسبت به بندهای رکابی دارد. افزایش تعداد برش و درز در و همچنین وجود پد سبب راحتی حرکتی کمتر ورزشکار در پایین نیم‌تنه خواهد شد. اعتبارسنجی نتایج تجربی با استفاده از توسعه‌ی مدل الکترومکانیکی ارائه شده در تحقیق نیز نتایج را تأیید می کند و حاکی از ضریب همبستگی بالا (بیشتر از ۷۵٪) بین نتایج تجربی و مدل است.

واژه های کلیدی: نیم‌تنه‌ی ورزشی، جابجایی سینه، راحتی حرکتی، حسگر نخ فلزی، مدل الکترومکانیکی.