Res Intell Manuf Assem, 2024, 2(1): 70-84
DOI: 10.25082/RIMA.2023.01.004

RESEARCH ARTICLE

Bioenergetic analysis and anthropometric evaluation of bra-breast interface for improved design and breast health

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Received: May 16, 2024;
Accepted: July 29, 2024;
Published: August 5, 2024.

Citation: Hamandi F, Pooler T, Runser A, et al. Bioenergetic analysis and anthropometric evaluation of bra-breast interface for improved design and breast health. *Res Intell Manuf Assem*, 2024, **2**(1): 70-84. https://doi.org/10.25082/RIMA.2023.01.004

Abstract: Bioenergetics analysis of bra-breast Interface is an important technique for improving the design of bras and promoting breast health and comfort during physical activity. The objective of this study is to evaluate the compatibility between the anatomy of the breasts and bra. The study encompasses breast anthropometry via measurement. A measurement topology was proposed to determine breast mass, volume, shape, and asymmetry under loading (with-bra) and unloading (without-bra). Using the anthropometric data, the bioenergetics of the breasts were determined and compared to the rest of the body. From the bioenergetic analysis, a larger breast could require up to 69 J of energy during walking. The average mass of a breast ranges from 500 to 1000 g. Assuming breast shape to be standard, semi-conical, semi-spherical and semi-elliptical, breast volume was determined where semi conical and semi spherical breast shapes consistently predicted lower bound volume for each breast, whereas the standard and semi elliptical breast shapes predicted higher volume for the same breasts measurements. Mathematically, the medial-lateral boundaries of the breast were described by a secant of a curve, aligned on the coronal plane, causing eccentric loading when the two breast nipples were on different transverse planes. When this variation was more than 5% volume change, asymmetric breast shapes occurred and was responsible to displace bra heterogeneously compromising fit and support. A non-linear, leaf-function describing the relationship between the breast radius and volume invoked at a given body weight. In general, the current design for a bra assumes that the breasts are symmetrical, though the current investigation proves that this is not the case. The bra needs to be redesigned to better fit women, since left and right sides are not symmetrical. This is a significant problem today, as it is estimated that nearly 80% of women wear incorrectly- sized bras; 70% wore bras that are too small, and 10% wore bras that are too big. Current investigation highlights the crucial importance of incorporating the distance between the nipples into bra design to achieve optimal support, comfort, symmetry, and minimize breast movement. It ensures that the bra cups are positioned optimally to provide effective support and enhance the natural shape of the breasts. If the current bra models are redesigned, the amount of discomfort in women could potentially decrease.

Keywords: breast anthropometry, bra design, bra-breast interface, breast symmetry

1 Introduction

Women throughout history have worn bras in order to support breasts. This support is a key in preventing breast pain as well as unnecessary pulling of the skin during daily life activities [1], while in elastic conditions occurring with small masses may introduce viscoelastic or hyper elastic strains for larger shapes resulting in permanent deformation. In 1914, Mary Phelps Jacob created and patented a design for the first modern bra [2]. Since the creation of the first bra, the structure and design has changed drastically. Bras have many functions such as support, aesthetics/fashion, or assistance with breastfeeding. Currently, bras are being mass-manufactured under the assumption that breasts are symmetrical and evenly spaced in terms of cup sizes [3]. These sizes are standard, but many factors go into the fit of bra including the height, width, or degree of sagging of the chest [4]. Since each breast is different, obtaining the fit and ideal way to manufacture bras can be challenging. Female breasts are extremely well understood and well documented. Breast anatomy, which is influenced by hormonal changes in the body during adolescence, pregnancy, or menopause. Even though the anatomy of the breast is fairly standardized, breasts are not; from woman to woman, breasts can differ in terms of size, shape, and handedness [5]. Understanding the mass of the breast as a source of force can lead to understanding the biomechanics consideration. The various tissue types of the components of the breast all have their own mechanical properties and densities that can be factored into a biomechanical analysis of the breast in order to better understand the relationship between breast mass and force translated onto the breast tissue. Understanding the shape, size, and overall geometry of the breasts, as well as any differences that may be observed between a left and right breast, can help to define this relationship. Most fundamentally, breast may be divided into four quadrants, which are: upper inner, upper outer, lower inner, and lower outer, with the upper outer lobe containing the majority of breast volume [6,7]. During adolescence, female breasts develop and undergo many changes. Until puberty, the breasts are considered to be "underdeveloped". At the start of puberty, ovarian estrogen and progesterone production begins, and thus an increase is observed in the blood concentration of those hormones throughout the body. As a result, the breasts enlarge due to the development of the mammary glands and increased deposition of adipose tissue, also referred to as fatty tissue [6]. As the breasts enlarge during development, the inframammary fold also develops and becomes a defining boundary of the breast [8]. The inframammary fold anchors the breast to the thoracic wall and defines the inferior boundary of the breast [8]. The histology of the inframammary fold is not well-understood or well-documented. In order to study the histology of this tissue, cadaver tissue is often used rather than studying live subjects [8]. Study of this cadaver tissue has led to some understanding of the composition of the inframammary fold tissue. As well as normal development of the breasts throughout puberty and adolescence, pregnancy and menopause also play a significant role in changing the breasts and their anatomy. Further development of the breasts during pregnancy consists of breast enlargement, and a consequent increase in breast volume and density, as well as dilation of superficial veins and darkening of the nipple-areola complex [6]. Throughout pregnancy, stromal elements of the breast slowly transition to epithelium. After delivery of the child, lactation occurs due to dramatic decreases in estrogen and progesterone. As the baby is weaned, stromal elements begin to atrophy and the overall size of the breast decreases [6]. During menopause, ductal and glandular elements involute and the breasts become mostly fat and stroma. Over time, even this tissue decreases, which leads to loss of breast contour as the breasts shrink further. The suspensory ligaments within the breasts also relax with time, leading to breast ptosis or sagging [6,8]. Throughout the ages, bras have been used to combat this ptosis. Therefore, study of bra-breast biomechanics is a function of a given reference; age, pregnancy and menopause and needs to be understood fully. The average mass and volume of each breast has been studied for various bra sizes in literature [9,10]. It has been found that the average mass of a small-to-moderate breast is approximately 500g while larger breasts average approximately 750-1000g [9,10]. This large mass in large breasts can be translated into force that the breast tissue is subjected to even when the woman is just standing. The average force on the breasts due to their weight (when subject is standing) is found to be approximately 11.7 ± 4.6 N for large breasts [10]. Frequently, this force being projected onto the breast tissue is a result of wearing a bra, especially a bra with an underwire in it. It is likely that activities of daily living increase this force many folds at the breast mass center, however, at the tissue and glands it is likely that the forces developed may be elastic, visco-elastic, and/or hyper-elastic. Limited data is available in the literature investigating breast tissue under those constitutive conditions.

2 Bra Design Issues

A bra is a very complicated device made from clothing of different stiffness and mechanical properties. It is estimated that a bra can have between 20 and 45 different compartments such as the underwire, straps, bands, hooks, etc. The materials used to manufacture the lining, padding, straps, and underwire have changed over time. Most commonly, bras contain underwires, which are sewn into the fabric of the bra at the base of the cups. The underwire of the bra helps to provide extra support and lift of the breasts. Underwires can be made from either plastic or metals, but plastics are not usually considered in the market because they do not have the strength to achieve the level of support that metal underwires offer [11]. Metal underwires are typically constructed with steel or nickel-titanium (Nitinol), which is a shape memory alloy [12]. Steel has very high yield and tensile strength values, which makes it very durable when manufacturing a bra. The yield strength and tensile strength of steel are 205 MPa and 500 MPa, respectively [13]. Steel underwires can provide a durable design for a bra underwire to prevent breaking. Nickel-titanium alloys are unique because they have shape-memory abilities, meaning that these materials can return to their original shape after being subjected to a load [14].

Nitinol has yield and tensile strength values comparable to steel approximately 195 MPa and 895 MPa, respectively [15]. Utilizing both materials is beneficial when manufacturing bras. While bras can provide support to breasts, bras can also cause a lot of discomfort and pain to women. Underwire bras can irritate the skin and cause breast pain. Since underwire bras are made to constrict the breasts, they can contribute to clogged milk ducts in breastfeeding women [16]. Because metal underwires are rigid, they cannot change easily to fluctuating breast size that may occur during pregnancy, breastfeeding, menstruation, or aging. Considering that most women wear bras every day, it is important to ensure that bras fit correctly. However, it is estimated that nearly 80% of women wear incorrectly- sized bras; 70% wore bras that were too small, and 10% wore bras that were too big [17, 18]. Incorrectly fitting bras may contribute to breast pain and lower thoracic pain due to the breast being improperly supported. The objective of this study was to investigate the anthropometric measurements of the breast and analyze the breasts in the context of biomechanics in order to establish and evaluate the relationship between mass/weight and projected force. Ultimately, the goal of this research was to obtain measurements of the breasts under loading (with-bra) and unloading (without-bra) conditions. These measurements were necessary to be able to compare natural and forced breast geometry as well as to be able to compare between the anatomy of the left and right breast. Detailed measurements of both breasts were compiled so that they could be statistically analyzed to determine if there is a true difference in geometry (shape and size) among the breasts of most women.

2.1 Factors Affecting Bra Selection

In order to understand the main factors affecting selecting a bra, a survey was conducted. The main questions were about the number of hours the bra worn per day, and what subject considers when selecting/ purchasing a new bra. Fourteen factors affecting bra purchasing were investigated (Figure 1). These factors are comfort, bra stays in place, fit, appearance under clothes, support, discreetness, shoulder straps, breast shape, fabric, breast lift, color, price, matching underwear, and the brand. The results exhibited that the comfort of the bra was the most important factor among all the subjects (97.6 %), and (95.2%) of them thought having a bra that fits perfectly is important. On the other hand, only (11.9%) and (2.4%) thought that the brand of the bra or having matching underwear could be important, respectively. In general, the comfort factor is extremely important to be taken into consideration when designing a bra as 72% of women wear the bra for more than 10 hours per day.

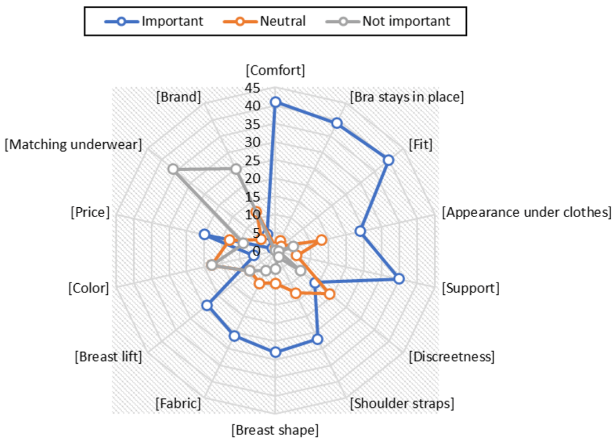

Figure 1 Chart showing the importance of each factor for subjects when buying a new bra

It has been assumed for years that all body types and breast sizes – have perfectly symmetrical breasts that with sustained usage cause breast pain, thoracic pain, as well as back pain. Through our current study, it can be asserted that all women have a handedness, meaning that one of their breasts is larger than the other unable to achieve the support that their bodies need without experiencing this chronic pain. Engineering a bra must involve anthropometric and bioenergetic considerations in their design. Further study is needed in order to understand how these forces affect breast tissue and associated medical conditions.

3 Experimental Work

The research was conducted in strict accordance with the ethics protocol approved by the Health and Research Board (#06563) at Wright State University, USA. The data of 43 subjects were included in this study, mean age and standard deviation 44 ± 18 years and weight 182 lb ± 43. The experimental part of this research included developing a testing module to measure breast anthropometry (Discussed in section 3.1). Using these parameters, we determined the breast mass, volume, shape, asymmetry, and gathering measurements of breasts under loading (with-bra) and unloading (without-bra) conditions. Additionally, the breast shape and volume were investigated. Using anthropometric data, the bioenergetics of the breasts were calculated and compared to the rest of the body.

3.1 Acquisition of Breast Anthropometric Data

The geometry of each breast was measured with and without bra. For the purposes of this study, all subjects were instructed to wear an underwire bra during the measurements. The main breast anthropometric measurements points used in this study are shown in Figure 2 and Table 1, which are the sternal notch, the nipple, the medial and the lateral side of the breast, superior and inferior point of the breast, and the axilla (armpit). These points were chosen to represent all the three planes of the breast the frontal, sagittal, and transverse planes, as discussed in Zhou et al. [19].

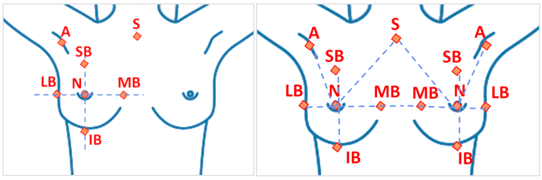

Figure 2 The main breast anthropometric measurements points (left). The sketch of the obtained anthropometric measurements (right)

Table 1 The main breast anthropometric measurements points and their descriptions

Point	Description
S	Sternal notch
N	The nipple
MB	Medial side of the breast
LB	Lateral side of the breast
SB	Superior point of the breast
IB	Inferior point of the breast
A	Axilla (armpit)

The anthropometric measurements defining the fit of the bra were established according to Figure 2 (Table 2 shows the description) and were measured on the subjects both physically, using a tape measure, as well as digitally, using a 3D body scanner. These measurements are *A-N, MB-MB, LB-LB, MB-LB (curve), MB-LB, IB-SB (curve), IB-SB,* Δ, *Band,* and *Bust*. The resulting data were used to evaluate the similarity between the left and right breast in terms of both size and shape. These measurements defined the geometry being forced by bra and considered to be loaded asymmetrically. In this experiment, liquid eyeliner was used to trace key points, lines, and curves of the bra so that the measurements taken while the volunteers were wearing a bra could be replicated as accurately as possible when the subjects were not wearing their bra. These marks could also be made with a regular marker or possibly with tape, though it was found that the eyeliner would be less likely to stain than a marker and less painful to remove from the subjects' skin than tape. Measuring with respect to these points helped to ensure consistency between loading and unloading conditions. Under unloaded conditions, the geometry of the breasts was assessed using a tape measure and the 3D body scanner. The purpose was to analyze and determine the similarity between the left and right breasts. The 3D scanning was conducted without the bra, and the body position was standardized across all volunteers to ensure the comparability of measurements obtained by hand. The scanning process is usually completed in less than a minute, therefore the process was not time-consuming. MATLAB code was developed to obtain the measurements from the scanned 3D models enabling the calculation of breast volume and surface area.

3.2 Acquisition of Breast Shape and Volume

Breast shape is different for each breast depending upon the age and marital status as well as having children [27]. In this study, four different shapes were chosen, which are standard

Table 2 The obtained breast anthropometric measurements and their descriptions

No.	Measurements	Description
1	S-N	Sternal notch to the nipple
2	N-N	The distance between the nipples
3	MB-N	Medial side of the breast to the nipple
4	LB-N	Lateral side of the breast to the nipple
5	SB-N	Superior point of the breast to the nipple
6	IB-N	Inferior point of the breast to the nipple
7	A-N	Axilla (armpit) to the nipple
8	MB-MB	The distance between the two medial sides of the breast
9	LB-LB	The distance between the two lateral sides of the breast
10	MB-LB (curve)	The curve distance between the medial sides of the breast to the lateral side
11	MB-LB (line)	The distance between the medial sides of the breast to the lateral side
12	IB-SB (curve)	The curve distance between the inferior sides of the breast to the superior side
13	IB-SB (line)	The distance between the inferior sides of the breast to the superior side
14	Delta (Δ)	The distance between the two nipples planes
15	Band	The distance under the bust around the ribcage
16	Bust	The distance around the chest, at the fullest point of the bust

(SV), semi conical (SCV), semispherical (SSV), and semi elliptical (SEV) shape. Additionally, the volume of the breast with bra (WBV) was calculated considering hemispherical shape will prevail. The equations that were used to calculate the volume (*V*) and surface area (*S.A.*) for each breast shape were:

For Standard Shape:

$$\mathrm{S.A.} = \pi\left(\mathrm{R}^* + \mathrm{r}^*\right)\mathrm{l} + \pi \mathrm{R}^{*2} + \frac{1}{2}(4\pi \mathrm{r}^2) \tag{1}$$

$$\mathrm{V} = \frac{1}{3}\pi \mathrm{h}(\mathrm{R}^{*2} + \mathrm{r}^{*2} + \mathrm{R}^*\mathrm{r}^*) + \frac{1}{2}(\frac{4}{3}\pi \mathrm{r}^3) \tag{2}$$

For Semi Conical Shape:

$$\mathrm{S.A.} = \pi\left(\mathrm{R}^* + \mathrm{r}^*\right)\mathrm{l} + \pi \mathrm{R}^{*2} \tag{3}$$

$$\mathrm{V} = \frac{1}{3}\pi \mathrm{h}(\mathrm{R}^{*2} + \mathrm{r}^{*2} + \mathrm{R}^*\mathrm{r}^*) \tag{4}$$

For Semi spherical Shape:

$$\mathrm{S.A} = \frac{1}{2}(4\pi \mathrm{r}^2) \tag{5}$$

$$\mathrm{V} = \frac{1}{2}(\frac{4}{3}\pi \mathrm{r}^3) \tag{6}$$

For Semi Elliptical Shape:

$$\mathrm{S.A} = 2\pi(\frac{(\mathrm{A}*\mathrm{B})^{1.6075} + (\mathrm{A}*\mathrm{C})^{1.6075} + (\mathrm{B}*\mathrm{C})^{1.6075}}{3})^{\frac{1}{1.6075}} + \pi*\mathrm{B}*\mathrm{C} \tag{7}$$

$$\mathrm{V} = \frac{2}{3}*\pi*\mathrm{A}*\mathrm{B}*\mathrm{C} \tag{8}$$

Where (*r*) is the radius of breast, (*h*) is the longitudinal height of breast, (R^*) is the radius of the larger base. (r^*) is the radius of the smaller base. (*l*) is the slant height of the frustum that can be calculated using the Pythagorean theorem ($l = \sqrt{h^2 + (R^* - r^*)}$), (*A*) is the bisected axis that equals to ($\frac{2\times(\mathrm{MB-LB})_{\mathrm{curve}}}{\pi}$), (*B*) is the second semi axis that equals to ($\frac{(\mathrm{IB-SB})}{2}$), and (*C*) is the third semi axis that equals to ($\frac{(\mathrm{MB-LB})_{\mathrm{curve}}}{\pi}$).

3.3 Bioenergetics Analysis

Bioenergetics analysis of the bra-breast interface is an important technique for improving the design of bras and promoting breast health and comfort during physical activity. To emphasize the importance of having a well fitted bra, we performed a bioenergetics analysis of the breasts and their motion. The goal of this part of the study was to observe how much of one's energy consumed by the breasts as a result of motion during daily activities. Equation (9) was used to calculate the total energy consumed, per breast, when the breast was moving at given velocity (v). Three velocity values were examined: 0.12, 0.15, and 0.18 m/s for normal walking, jogging, and being active, respectively. In static condition, the potential energy of the breast is constant and does not change during movement as it is located at the center of mass of the breast. The motion of the breasts moving at specified velocity was considered in terms of translational motion (left, right, up, down motion) and rotational (angular motion). Energy from each type of motion was considered with the breasts' gravitational potential energy, which is due to both geometry of the breasts as well as other factors (height, weight, etc.). For the current analysis, we assumed that there is no plasticity, and the breast volume stays constant during motion. Additionally, we asked all subjects to wear underwire bras so their breasts would have hemispherical shapes under the bra, so we were able to apply the measurements of that shape in our bioenergetic calculations. The total energy removed from the body by the breasts during motion can be described as the sum of the translational, rotation, and potential energies, calculated via the equations:

$$\mathrm{E_{Total}} = \mathrm{E_{Translational}} + \mathrm{E_{Rotational}} + \mathrm{E_{Potential}} \tag{9}$$

Where $\mathrm{E_{Total}}$ is the total energy, $\mathrm{E_{Translational}}$ is the Translational energy, $\mathrm{E_{Rotational}}$ is the Rotational energy, and $E_{Potential}$ is the Gravitational Potential energy. Overall, the contributions of these different types of energy to the total energy balance of the breast can vary depending on factors such as metabolic rate, physical activity level, and body position. Accurately estimating the contributions of each type of energy requires a detailed understanding of the physiological and biomechanical processes involved.

$$\mathrm{E_{Translational}} = \frac{1}{2}\mathrm{mv}^2 \tag{10}$$

Where (m) is the weight, and (v) is the velocity. This equation assumes that the breast tissue is moving in a straight line with a constant velocity. In reality, the motion of the breast tissue may be more complex and involve changes in direction or speed. However, this equation provides a simple estimate of the translational energy of the breast based on its mass and velocity.

$$\mathrm{E_{Rotational}} = \frac{1}{2}\mathrm{I}\omega^2 \tag{11}$$

Where (I) is the is the moment of inertia of the breast tissue in kilograms times meters squared (moment of inertia of hemisphere) and calculated using equation (12), and (ω) is the angular velocity of the breast tissue in radians per second and calculated as (v/r). However, it's important to note that the breast is not a rigid body, and its motion is influenced by a variety of factors such as tissue elasticity, muscle activity, and gravity. Therefore, the breast may not move in a perfectly circular path, and the radius of the circular path may be difficult to define precisely. Additionally, the breast may move with a combination of translational and rotational motion, which can complicate the analysis. The rotational energy equation assumes that the breast tissue is rotating around a fixed axis, such as the center of mass of the breast or a point on the skin surface. In reality, the motion of the breast tissue may be more complex and involve changes in axis or rotation speed. However, this equation provides a simple estimate of the rotational energy of the breast based on its moment of inertia and angular velocity:

$$\mathrm{I} = \frac{\mathrm{mr}^2}{5} \tag{12}$$

Where (r) is the radius of the breast.

Regarding the potential energy, this type of energy is related to the position of the breast tissue in a gravitational field. The potential energy of the breast can be estimated based on the height of the tissue above a reference point, such as the ground or the center of mass of the body. Potential energy is typically a small contributor to the overall energy balance of the breast, but it may be more significant in situations where the breast is subject to large changes in height, such as during physical activity:

$$\mathrm{E_{Potential}} = \mathrm{mgh} \tag{13}$$

Where (m) is the mass of the breast tissue in kilograms (kg), (g) is the acceleration due to gravity, which is approximately 9.81 m/s^2 on Earth, and (h) is the height of the breast tissue above a reference point in meters (m). This equation assumes that the breast tissue is treated as a point mass, which is lifted to a certain height above the reference point against the force of gravity. In reality, the breast tissue is more complex and may have varying densities and shapes, which can affect its potential energy. However, this equation provides a rough estimate of the potential energy of the breast based on its mass and height above a reference point.

In order to complete this analysis, some anthropometric data was used to approximate average breast density and size (volume and weight) as a function of age [20, 21]. These data were used to calculate the average breast mass a function of age, which were substituted into the equations (9-13) in order to calculate average translational, rotational, and potential energy for various age groups. Data from women aged > 29, 30-39, 40-49, 50-59, 60-69, 70-79, and > 80 were grouped together. The bioenergetics analysis was then performed on each of the 7 age groups and each of the three velocity values of interest.

4 Results

4.1 Acquisition of Breast Anthropometric Data

The data was collected for each breast with or without bra. Measurement locations were determined based on the landmarks defined in Figure 3. When the landmarks differ, they cause breast and bra dynamics to change. The recordings were measured with a standard ruler, as well as scanned through a 3D scanner. The measurements were recorded on both the right and left breasts, and with/without a bra on. The data collected for the measurements can be seen in Table 3.

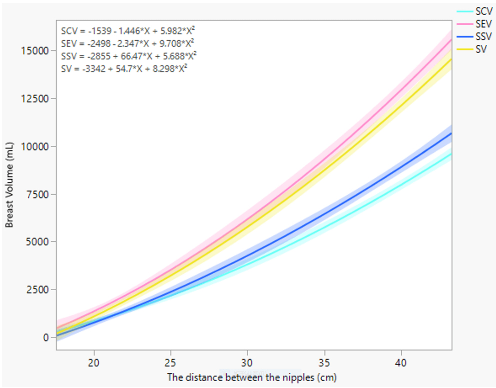

Figure 3 The distance between the nipples in different breast shapes (Standard (SV), Semi spherical (SSV), Semi elliptical (SEV) and Semi conical (SCV)).

Table 3 Breast Anthropometric Data results (cm)

	Measurement	Unloaded (Without Bra)		Loaded (With Bra)	
		Mean	SD	Mean	SD
	The distance between the nipples	24.16	5.14	20.36	7.26
	The curved distance between the two Lateral sides of the breast points	50.33	17.32	57.95	15.18
	The distance between the two Medial sides of the breast points	2.76	1.32	2.14	0.58
	The distance between the two nipples planes	1.33	0.63	0.41	0.16
Right Breast	Axilla (armpit) to the nipple	22.92	5.84	19.08	2.44
	Lateral side of the breast to the nipple	16.36	5.02	12.48	4.83
	Medial side of the breast to the nipple	17.17	5.68	10.16	3.65
	The curve distance between the Medial and Lateral sides of the breast	30.50	8.77	26.57	5.46
	Inferior point of the breast to the nipple	9.85	2.63	11.42	2.84
	Sternal notch to the nipple	27.98	4.82	22.86	5.03
	The line distance between the Medial and Lateral sides of the breast	15.84	2.99	16.06	3.20
	The distance between the Superior and Inferior points of the breast	10.68	2.62	15.93	2.88
Left Breast	Axilla (armpit) to the nipple	22.66	5.76	18.97	2.83
	Lateral side of the breast to the nipple	15.54	4.67	12.18	4.03
	Medial side of the breast to the nipple	17.18	5.72	10.39	3.47
	The curve distance between the Medial and Lateral sides of the breast	30.63	8.82	26.83	5.13
	Inferior point of the breast to the nipple	9.70	2.80	11.18	2.45
	Sternal notch to the nipple	28.27	5.22	22.74	4.96
	The line distance between the Medial and Lateral sides of the breast	16.42	2.98	17.05	2.94
	The distance between the Superior and Inferior points of the breast	10.99	2.50	16.85	2.56

4.2 Breast Volume Results

After the data and measurements were collected, the volume, diameter, surface area, and mass were calculated for each breast, for each volunteer. Four different breast shapes were assumed and the volume was calculated and compared with different bra measurements. These measurements were chosen because they had significant effect on the breast volume despite the shape, as the volume increased with the increment in the measurements (shown in Figure 3 & 4). These charts illustrate that there was no significant difference between the standard and semi ellipsoid shapes and no difference between semi spherical and semi conical shapes. It can be noticed that there was a significant difference between semi ellipsoid and semi conical shapes, which means that knowing the shape of the breast is as important as taking the measurements, and it is critical to take the shape of the breast into consideration when designing, selling, or purchasing a new bra. On the other hand, the volumes measured from the 3D scanned (SDV) models were less than the calculated volumes despite the shape, but with no significant difference ($p > 0.05$), as shown in Figure 5. The reason for that could be due to the difference in each breast shapes or the human error during the hand measurements. Additionally, Figure 6 shows that the volume of the breast decreases drastically when the bra is on (WBV) as the breast would be compressed firmly inside the bra cup. When we compared between the volume of breast with and without the bra for the same subjects, it can be noticed that some subjects have sgnificant diffrences in volume.

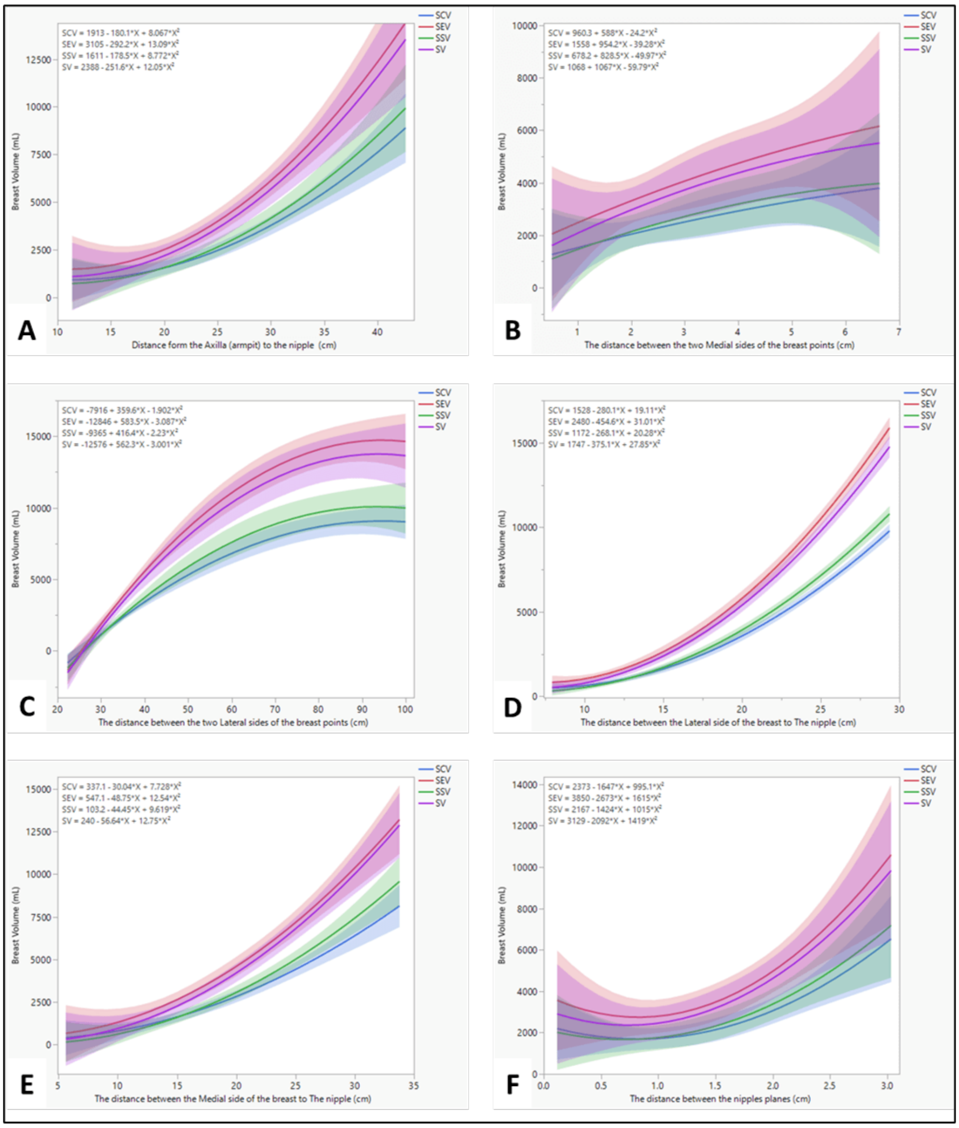

Figure 4 (A) Axilla (armpit) to The nipple in different breast shapes. (B) The distance between the two Medial sides of the breast points in different breast shapes. (C) The straight distance between the two Lateral sides of the breast points in different breast shapes. (D) Lateral side of the breast to the nipple in different breast shapes. (E) Medial side of the breast to the nipple in different breast shapes. (F) The distance between the nipples' planes in different breast shapes. Where Standard (SV), Semi spherical (SSV), Semi elliptical (SEV) and Semi conical (SCV) breast shapes.

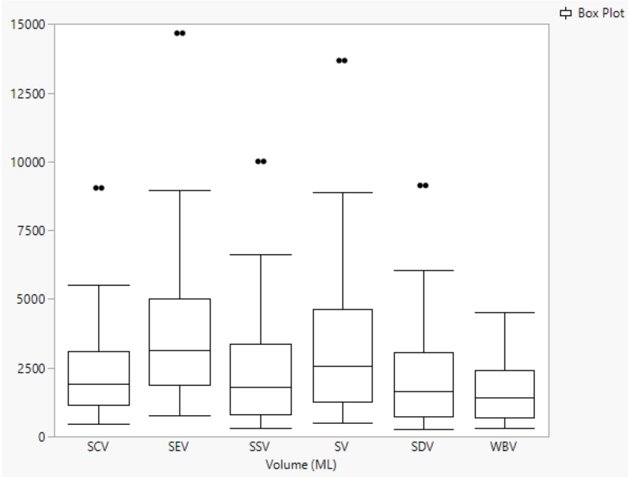

Figure 5 The calculated volume for the breast with bra (WBV) vs different shapes (Semi conical (SCV), semi ellipsoid (SEV), semi spherical (SSV), standard (SV)) *vs* the volume measured from 3D scanned breast models (SDV).

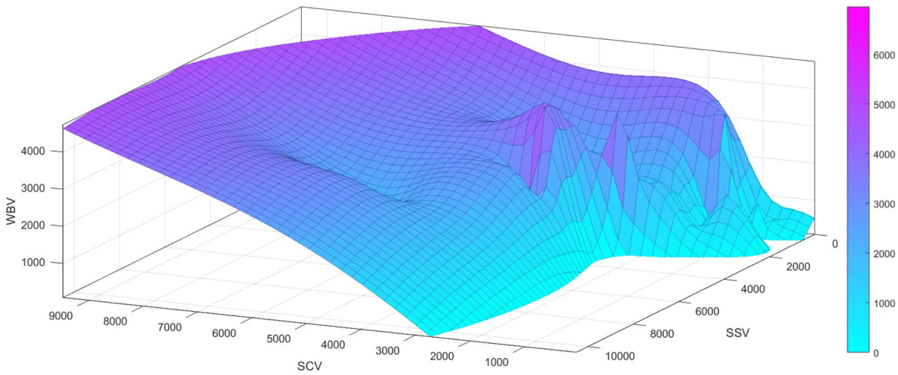

Figure 6 With bra volume (WBV) *vs* without bra volumes (SCV and SSV)

A sensitivity analysis was performed to investigate the effect of the body weight and the breast radius on the breast volume. The results indicated that the volume increased as the radius of the breast increased. On the other hand, there was no relationship between the weight of the subject and the breast volume.

Investigating the asymmetry of the breast is very significant, as indicated by the survey results. The findings revealed that 46% of participants exhibited visible asymmetry, 14% had some unnoticeable asymmetry, and 40% either had no asymmetry or were unsure. These statistics highlight the prevalence of breast asymmetry among the participants. It emphasizes the need to address this issue seriously when designing bras. Interestingly, despite the noticeable asymmetry, the results indicated no significant difference in volume between the right and left breasts.

4.3 Bioenergetics Results

Based on anthropomorphic data, the total energy requirements for each breast, relative to band and cup size, can be determined by using the equations 9-13. The results of total, translational, rotational, and potential energies are shown in Table 4 for the examined velocity value (0.18 m/s). The energy was compared with band size for different cup sizes, as shown in Figure 7. Additionally, the energy was compared with the cup diameter and displayed that as the cup diameter increases, the energy increases, as shown in Figure 8.

5 Discussion

Nowadays, bras are being mass-manufactured under the assumption that breasts are symmetrical and evenly spaced. Companies manufacturing bras using measurement standards for band size and cup size only. These sizes are considered as a standard, but many factors should be considered to fit a bra including the height, width, or degree of sagging of the chest. This

Table 4 Energy calculations for cup and band size

Cup Size	Cup diameter (cm)	Volume of one cup	$E_{potential}$ 0.18 (J)	$E_{rotational}$ 0.18 (J)	E_{trans} 0.18 (J)	E_{total} (J)
A	9.7	240 cc (0.51 US pt)	2.107	0.005	3.48	5.592
B	10.6	310 cc (0.66 US pt)	2.744	0.005	4.54	7.289
C	11.4	390 cc (0.82 US pt)	3.43	0.005	5.67	9.105
D	12.3	480 cc (1.0 US pt)	4.214	0.005	6.97	11.189
E	13.1	590 cc (1.2 US pt)	5.39	0.01	8.91	14.31
F	14	710 cc (1.5 US pt)	6.37	0.01	10.53	16.91
G	14.8	850 cc (1.8 US pt)	7.35	0.015	12.15	19.515
H	15.7	1,000 cc (2.1 US pt)	8.82	0.02	14.58	23.42
I	16.5	1,180 cc (2.5 US pt)	10.29	0.02	17.01	27.32
J	17.4	1,370 cc (2.9 US pt)	12.25	0.03	20.25	32.53
K	18.2	1,580 cc (3.3 US pt)	13.72	0.03	22.68	36.43
L	19	1,810 cc (3.8 US pt)	16.17	0.04	26.73	42.94
M	19.9	2,060 cc (4.4 US pt)	18.13	0.045	29.97	48.145
N	20.7	2,340 cc (4.9 US pt)	20.58	0.055	34.02	54.655
O	21.6	2,640 cc (5.6 US pt)	23.52	0.065	38.88	62.465
P	22.4	3,000 cc (6.3 US pt)	25.97	0.075	42.93	68.975

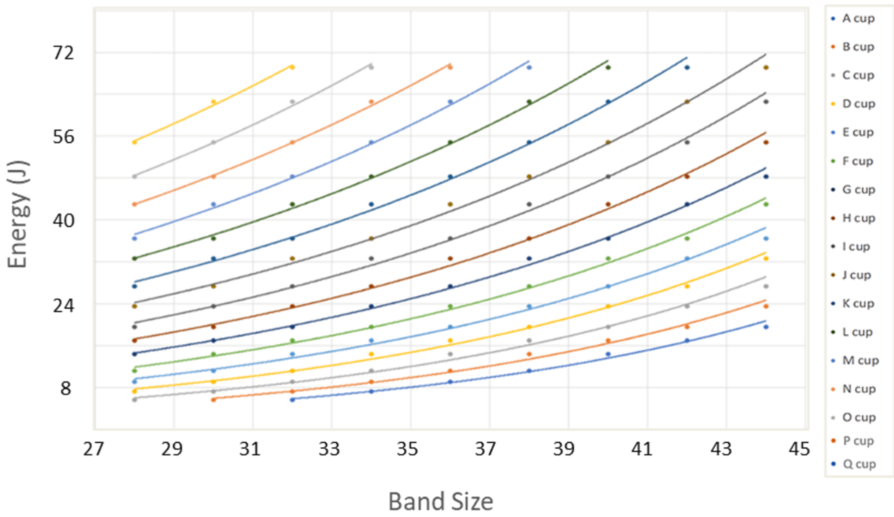

Figure 7 Energy *vs* bra size

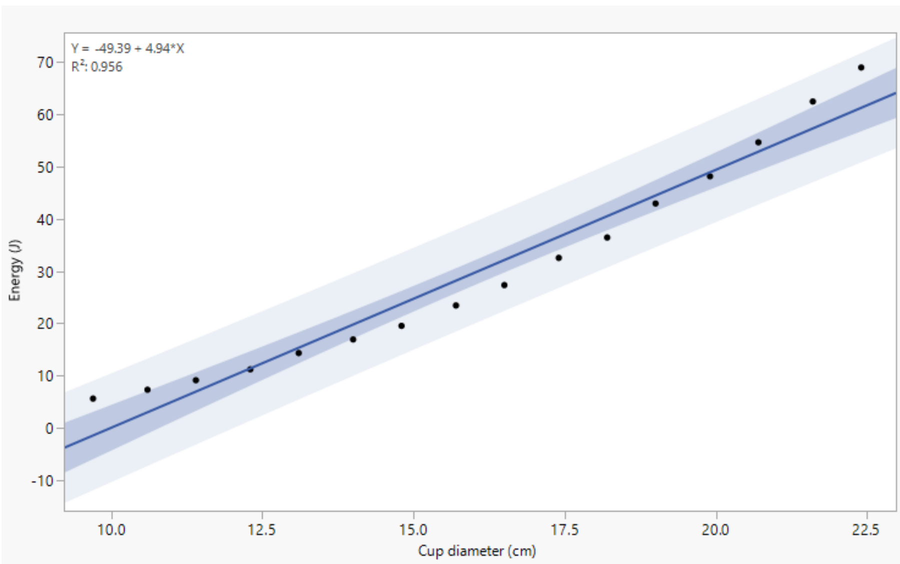

Figure 8 The energy *vs* cup diameter

study investigated the compatibility between the anatomy of the breasts and bra. The experiment encompasses breast anthropometry via measurement. A measurement topology testing module was proposed to determine breast mass, volume, shape, and asymmetry under loading (with-bra) and unloading (without-bra). Using the anthropometric data, the bioenergetics of the breasts were determined and compared to the rest of the body. The main breast anthropometric measurements landmarks used in this study are *S, N, MB, LB, SB, IB,* and *A*. These landmarks are necessary to be able to compare natural and forced breast geometry as well as to be able to compare between the anatomy of the left and right breast. In addition, these landmarks were chosen to signify all the three planes of the breast in the frontal, sagittal, and transverse planes.

The anthropometric measurements defining the fit of the bra were *S-N, N-N, MB-N, LB-N, SB-N, IB-N, A-N, MB-MB, LB-LB, MB-LB (curve), MB-LB (line), IB-SB (curve), IB-SB (line),* Δ, Band and Bust. Comparing the measurements of the breast-bra interface in loaded and unloaded conditions reveals important findings. In the unloaded condition, the mean distance between the two lateral sides of the breast points is slightly higher at 36.19 cm, while in the loaded condition, it decreases to 34.92 cm. The mean distance between the nipples is significantly higher in the unloaded condition (24.16 cm) compared to the loaded condition (20.36 cm). Similarly, the mean curved distance between the two lateral sides of the breast points is significantly higher when the bra is worn (57.95 cm) compared to without the bra (50.33 cm). Regarding the distance between the two medial sides of the breast points, it is slightly higher in the unloaded condition (2.76 cm) compared to the loaded condition (2.14 cm). In contrast, the distance between the two nipples planes is significantly lower in the loaded condition (0.41 cm) compared to the unloaded condition (1.33 cm). When considering the individual breast measurements, the axilla (armpit) to nipple distance, medial side of the breast to nipple distance, and lateral side of the breast to nipple distance are significantly lower in the loaded condition for both breasts. The curve distance between the medial and lateral sides of the breast is slightly lower in the loaded condition for both breasts. Additionally, the inferior point of the breast to nipple distance is slightly higher in the loaded condition for both breasts. The sternal notch to nipple distance is significantly lower in the loaded condition for both breasts. The line distance between the medial and lateral sides of the breast is slightly higher in the loaded condition for both breasts. Lastly, the distance between the superior and inferior points of the breast is significantly higher in the loaded condition for both breasts.

The distance between the nipples is a crucial parameter to evaluate the bra-breast interface because it directly reflects the positioning and alignment of the breasts. In the unloaded condition (without a bra), the mean distance between the nipples is 24.16 cm, with a standard deviation of 5.14 cm. When a bra is worn (loaded condition), the mean distance decreases to 20.36 cm, with a slightly higher standard deviation of 7.26 cm, as illustrated in Figure 9. This measurement indicates that the bra has a significant effect on bringing the nipples closer together and influencing the overall breast positioning. The reduction in nipple distance when wearing a bra suggests that the bra provides support and compression, potentially impacting breast shape, symmetry, and comfort. Understanding the changes in nipple distance due to bra usage is crucial for designing bras that provide adequate support, fit, and comfort. It highlights the importance of considering nipple positioning and breast alignment when evaluating and improving bra designs for optimal breast health and satisfaction.

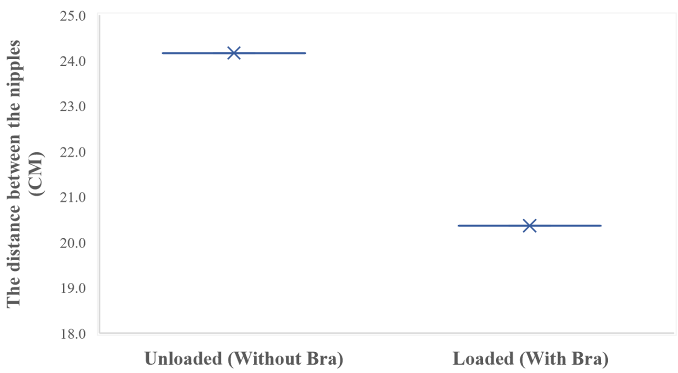

Figure 9 The distance between the nipples in loaded vs unloaded breast

Four different breast shapes were assumed in the current study (standard, semi elliptical, semi conical, and semi spherical), and the volume was calculated and compared with different bra measurements. Anthropometric measurements data shows that the semi conical and semi spherical breast shapes consistently predicted lower bound volume for each breast for all the volunteers, whereas the standard and semi elliptical breast shapes predicted higher volume for the same breast. The results demonstrated that as *N-N* increases, the volume of the breast increases (Figure 3), however, the ratio between the volume predicted by semi conical/standard, semi spherical/standard, and semi ellipsoid/standard was significant at the higher ranges of *N-N*, in contrary, there was no significant difference in the ratio between the semi conical and semi spherical breast shapes except in subjects where that distance was more than (27 cm). Also, it is evident that breast volume varies at a constant value of the *N-N*, indicative of changes in the sagittal breast geometry or shape while coronal plane coordinates are constant. Additionally, as the *A-N* distance increases, the volume of the breast increases (Figure 4A), however, the ratio between the volume predicted by semi conical/standard, semi spherical/standard, and semi ellipsoid/standard was significant at the higher ranges of the distance from *A-N*, where there was no significant difference in the ratio between the semi conical and semi spherical breast shapes except in subjects where that distance was more than (25 cm). We also observed that a parabolic fit may describe the relation between the breast volume and the *A-N*, where the volume reaches a peak point at the critical value of *A-N* being 25-27 cm. A smaller or larger value of *A-N* does not influence the breast volume. The same trend was seen when *MB-MB* or the *LB-LB* increase, the volume of the breast increases (4B and 4C, respectively). However, the ratio between the volume predicted by semi conical/standard, semi spherical/standard, and semi ellipsoid/standard was significant at the higher ranges of the distance with no significant difference in the ratio between the semi conical and semi spherical breast shapes except in the subjects where that *LB-LB* was more than (40 cm). Moreover, when *LB-N*, *MB-N* and *N-N* on the transverse plane increase, the volume of the breast increases (Figure 4D, 4E and 4F, respectively). In contrast, there was no significant difference was noticed in the ratio between the semi conical and semi spherical breast shapes except in the subjects where *LB-N* or *MB-N* was more than (20 cm) and the distance between the two nipples on the transverse plane increased 1.7 cm or above. Additionally, it was noticed that the volume of the breast decreases drastically when the bra is on as the breast would be compressed firmly inside the bra cup.

A sensitivity analysis was performed to investigate the effect of the body weight and the breast radius on the volume of the breast. The results indicated that the volume increased as the radius of the breast increased. On the other hand, there was no relationship between the weight of the subject and the breast volume. Figure 7 illustrates that body weight and the breast radius on the volume of the breast follow the "leaf behavior" where this behavior is widely used in literature to characterize the nonlinear behavior [22–25] to describe the large angle motion. The mathematical relation can be expressed as follows:

$$F_v(x_{b.w},\ y_{b.r}) = (T_{00})\ +\ (T_{10}) \times x_{b.w}\ +\ (T_{01}) \times y_{b.r}\ +\ (T_{20}) \times x_{b.w}^2 \\ +\ (T_{11}) \times x_{b.w} \times y_{b.r}\ +\ (T_{02}) \times y_{b.r}^2 \tag{14}$$

Where is the vol$F_v$ume of the breast, is the body$x_{b.w}$ weight, is the radi$y_{b.r}$us of the breast, and the coefficients (with 95% confidence bounds) were:

T_{00} = -1379 (-2.66e+04, 2.38e+04)
T_{10} = -51.74 (-25, 2415)
T_{01} = 36.87 (-151.4, 225.1)
T_{20} = -4.78 (-106.9, 97.32)
T_{11} = 1.59 (-7.18, 10.35)
T_{02} = -0.12 (-0.51, 0.27)

From the current investigation, it can be seen all of the data of the right and left breasts are different for the same measurement (Figure 7). However, the results indicated that there was no significant difference between the volume of the right and left breasts despite the noticeable asymmetry. To understand the asymmetry between the right and left breasts and if there is any effect on the breast, a comparison was made between the right and left breast of each subject with respect to different breast measurements. It was observed that as *N-N* increases the volume of the breast increases, nevertheless, there was no significant difference in ratio between the right and left breasts except in subjects where that distance was more than (33 cm). On the other hand, as the *N-N* on the transverse plane increases the volume of the breast increases. In contrast, there was a noticeable difference in ratio between the right and left breasts except in the subjects where that distance was between (0.9-1.7 cm). Moreover, when the straight or curved *LB-LB* increases, the volume of the breast increases with no significant difference between the right and left breasts. Nonetheless, when the *MB-MB* increases, the volume of the breast increases, however, there was a noticeable difference in ratio between the right and left breasts except in the subjects where this measurement was between (1.8-4.9 cm).

Using obtained anthropomorphic data, the energy requirements on each breast was determined. Based on Figure 9, larger breasts will require the highest energy required to constrain because the mass of the breast is increased. The largest size breast required nearly 68.97 J of total energy. The average energy required for a person walking is 372.54 ± 78.16 kJ [28]. While the energy requirement to move the breast is miniscule compared to the amount for walking, it shows the importance of having a supportive bra. We investigated how the energy changes as band size increases for different cup sizes. The results (Figure 8) indicated that the energy increases as the cup size increases. Women with (cup size A-G) demonstrated the least energy ranged between 5.59J- 19.52J, while women with (cup size N-P) demonstrated the highest energy ranged between 54.65 J – 68.79 J. Figure 9 displays an upward behavior for energy increment that is due to loading and unloading. If we observe the effect of mass and volume on energy, we can see that as the volume and mass increase, the energy increases, as illustrated in Figure 10. The main reason for women with bigger breasts (bigger cup size) to spend more energy is due to having more fatty tissue that fills the areas between connective tissue and glandular tissue. Moreover, eccentric position of two mass centers of gravities will result in one arm of the lever from fulcrum to be dominated causing higher work produced than the other, thus requiring additional support not only to contain it but also to resist the forces and displacement that arise from body movement.

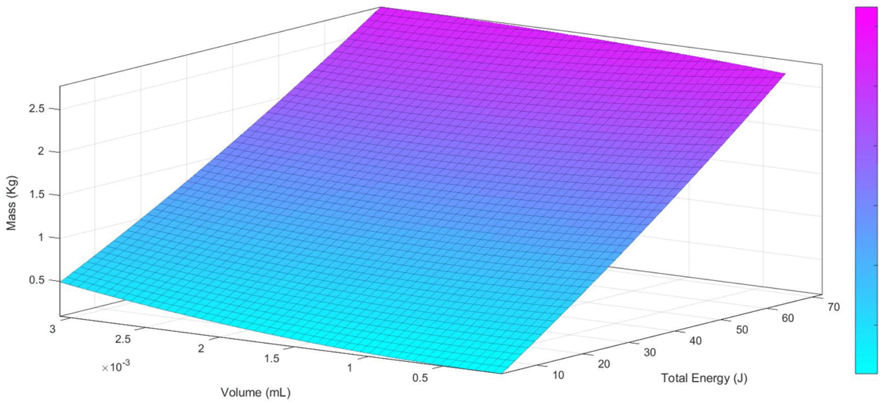

Figure 10 The mass *vs* energy and volume

Currently, the design for a bra assumes that the breasts are symmetrical [26]. The current investigation proves that this is not the case. The bra needs to be redesigned to better fit women, since left and right sides are not symmetrical. This is a substantial problem today, as it is estimated that nearly 80% of women wear incorrectly- sized bras; 70% wore bras that are too small, and 10% wore bras that are too big [17, 18]. Current investigation highlights the crucial importance of incorporating the distance between the nipples into bra design to achieve optimal support, comfort, symmetry, and minimize breast movement. It ensures that the bra cups are positioned optimally to provide effective support and enhance the natural shape of the breasts. If the current bra models are redesigned, the amount of discomfort in women could potentially decreases.

6 Conclusion

This study made significant contributions by integrating anthropometric measurements encompassing breast shape, asymmetry, and bioenergetic considerations involving mass, volume, density, and energy during daily activities. A testing module was developed to accurately measure breast anthropometry, enabling the determination of crucial parameters such as breast mass, volume, shape, asymmetry, and specific features (*S-N, N-N, MB-N, LB-N, SB-N, IB-N, A-N, MB-MB, LB-LB, MB-LB (curve), MB-LB (line), IB-SB (curve), IB-SB (line),* Δ*, Band*, and *Bust*). The findings of this study shed light on the limitations of the current commercially used measurements in defining breast geometry, emphasizing the need for a more accurate representation in bra design. It was evident that asymmetry is a prevalent factor that cannot be overlooked, as all the volunteers exhibited some degree of asymmetry, characterized by measurements differing by more than 5%. Thus, accounting for breast shape and considering asymmetry is crucial in the design, sale, and purchase of bras. Moreover, the research highlighted the significance of breast shape in determining volume, with semi-conical and standard shapes consistently indicating lower bound volumes compared to other shapes. While the energy required for breast movement was found to be negligible within the assumed parameters, the study emphasized the importance of a supportive bra that can resist breast movement, forces, and displacements. It was evident that as cup size increases, the energy requirement also increases. Therefore, when designing a bra, considering comfort is of utmost importance. Understanding the changes in the distance between the nipples resulting from bra usage is crucial for designing bras that provide adequate support, fit, and comfort. The study emphasized the need to consider nipple positioning and breast alignment in the evaluation and improvement of bra designs to promote optimal breast health and overall satisfaction. These insights challenge the validity of the current bra manufacturing process and call for a more comprehensive and personalized approach to bra design.

Conflicts of Interest

The authors declare no conflict of interest.

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