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DEVELOPMENT OF A TRANSDUCER FOR DETECTING PRESSURE LOAD  
BETWEEN A GARMENT AND THE BODY

by

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(ABSTRACT)

Garment pressure and its relation to the body is important in the fit and function of clothing. The purpose of this study was to develop and test a transducer to measure the perpendicular pressure between a garment (brassiere) and the underlying skin of the shoulders, breast and back. A transducer was developed through experimentation based on the principles of the Natick lab pneumatic bladders. The transducer was connected to a system which assisted in data collection.

This study revealed that it is possible to develop an inexpensive transducer that is reliable for data collection. The ability to evaluate garments in an objective manner could be combined with the subjective analysis of a model wearing a test garment. The analysis could provide information for redesigning a garment that is both functional and comfortable.

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CHAPTER I  
INTRODUCTION

Fuzek and Amons (1975, p. 121) define comfort as "the sensation of contented well-being and the absence of unpleasant feelings." Clothing comfort involves several factors, including garment fit (Morris, 1981). Garment pressure and its relationship to the body are important in the fit and function of clothing. For large busted women, a great amount of pressure may be exerted on areas of the shoulders and upper torso by garments such as brassieres or swimsuits. The ability to measure garment pressure at various levels and ascertain levels of pressure causing discomfort is particularly important to the design of tight fitting clothing. A review of literature indicates that there are a number of systems that are capable of measuring different load levels, or pressures on the human body, but none has been accepted widely for evaluating garment fit.

A variety of materials and devices have been used in pressure studies related to garments. Most incorporate a transducer that is connected to a display chart or graph. When a garment exerts pressure on the human body and contact occurs between the two components inside the transducer, an electrical circuit is completed. The wires leading from all of the transducers are joined into a single cable that

connects to the display panel.

Tomarazzo (1977) developed a load sensing system using an elastomeric material (rubber-like), Dynacon C, that exhibits conductivity as a function of pressure.

Costantakos (1981) used the Dynacon C transducer to examine and objectively identify various design features of nursing brassieres that cause pressure on the underlying skin. The Dynacon elastomeric material is no longer available.

The U. S. Army Laboratories, Natick, Massachusetts, (Natick Lab) have developed several pneumatic bladders with electrical contacts for detecting load thresholds (Barron, 1974). This type of transducer was used in the design and evaluation of Army gear that included a helmet and body armor. The large capital investment for an individual transducer prohibits its use in this research.

No device for measuring garment pressure was found to be available commercially at a price conducive to purchase by an independent designer or small apparel firm developing brassieres or swimsuits. The quantitative evaluation of pressure exerted by a garment on the human body could assist in the designing of apparel for the most desirable fit.

#### Purpose of the Study

The purpose of this study was to develop and test a transducer to measure the perpendicular pressure between a garment (brassiere) and the underlying skin of the

shoulders, breast and back.

### Objectives

1. To develop a transducer that is less expensive than those available at the time of this study.
2. To develop an apparatus that allows the transducer to be used in conjunction with a personal computer.
3. To characterize the reliability of pressure responses of the transducer; measuring the linear response, reproducibility, and hysteresis.
4. To pre-test the transducer by measuring selected pressure points between a brassiere and the skin of a large breasted woman.

### Assumption

1. Spurious shear forces will not be induced by the slight deformation of the garment necessary to accommodate the transducer.

### Limitation

1. The method of construction is appropriate for prototypes but may not be suitable for longevity of the transducer.

### Definitions

Compression- forced into less space.

Dynacon- An elastomeric material that exhibits conductivity as a function of pressure.

Force- an influence on a body, producing a change in movement or in shape or other effects.

Hysteresis- The phenomenon in which inflation pressure does not equal deflation pressure

Pressure- The force or load per unit area (ASTM,1986).

Shear force- The force applied into a plane.

Transducer- A device that converts one physical quantity (such as force, temperature, flow or displacement) into another physical quantity with more usable output characteristics. The term transducer is usually preferred to "sensor" or "detector" (Lyons, 1980, p. 147).

## Chapter II

### REVIEW OF LITERATURE

Comfort is a complex phenomenon. Wages (1974) identified three major aspects of comfort: physical comfort, psychological comfort, and sociological comfort. While the latter two aspects are highly subjective in nature, physical comfort may be measured both subjectively and objectively. Efforts have been made by the industry to develop objective means of assessing comfort (Kawabata, 1984).

Garment fit is one factor in the physical comfort of a garment. Morris and Prato (1981) conducted a study to evaluate the comfort and fit of denim jeans by preference evaluations and wear study results. Comfort ratings were found to be most dependent on the fit of the garment. When a garment does not fit properly, it may result in physical discomfort. It is in the best interest of the designer to minimize discomfort in garments. This review of literature describes the research that has been done relative to pressure exerted by garments on the skin and methods used to measure that pressure.

#### Compression Stress

The primary forces that affect the fit comfort of a garment are tension, compression and shear (Fourt and Hollies, 1970). Tension serves to elongate or expand the

material it acts on. The removal of an adhesive bandage is an example of tension acting on the skin. The opposite of tension is compression. The forces act to compress the material or skin. An elastic watchband illustrates a compressive force. As used here, tension and compression act perpendicular to the area of interest. Shear stress is defined as a force acting in the plane of the area of interest. If the individual wearing the watchband is sliding it onto her wrist, the example more accurately illustrates a combination of forces, compression and shear.

Various units may be used to measure pressure, or compression forces. Difficulty arises in trying to make quantitative comparisons between studies. Some investigators report results in ergs, others in milligrams or grams per square millimeter, and still others in displacements. A displacement can be explained as a membrane distortion (Verrillo, 1975). Since pressure is defined as "force or load per unit area" (ASTM, 1986), unless a researcher states the area over which a force is distributed, a result as a force can not be compared to a result as a pressure. For purposes of this review, measurements will be converted when possible to pounds per square inch (psi) to allow for comparison.

### Pressure and the Human Body

Under certain conditions of stimulation, displacements of the skin less than 1 micron (0.00004") are sufficient to arouse a sensation of touch (Verrillo, 1975). Threshold is the point at which a stimulus is of sufficient intensity to begin to produce an effect. Touch sensitivity thresholds for several areas of the female body have been reported by Weinstein (1968).

The "pressure sensations" that an individual feels are due to the deformation of tissues deeper than those necessary to stimulate the "touch" sensation (Brognia *et al.*, 1976). The nerve fibers in the body easily sense a small force concentrated above the fiber and send messages of discomfort to the brain, while a larger force over a larger area may not cause the nerve endings to send a discomfort signal to the brain. A high pressure on a small area of muscle, bone or blood vessel hampers movements more severely than the equivalent force spread over a large area.

Touch and pressure sensations are not uniform for all portions of the body. Proper fit and load distribution with respect to these different sensitivities is important (Costantakos, 1981). In general, areas of the body that have greater amounts of muscle or fat present can tolerate more pressure than bony areas.

Weinstein (1968) measured touch sensitivity at twenty body sites of twenty male and female subjects. The results indicated that the face is the most sensitive part of the body. The trunk is next, followed by the fingers and arms. The lower extremities were found to be the least sensitive body parts. Males and females showed similar trends in sensitivity, but in general, women were found to be more sensitive to touch than men.

Denton (1971) calculated that the discomfort threshold for garments is between 0.4 and 0.7 psi. Based on this research, Powderly (1978) reports, but does not reference, previous research that indicates a close fitting garment should exert no more than 0.5 psi pressure to be comfortable. Tolerance levels vary widely through a given cross-section of people. Factors that may influence a difference in tolerance level include age, gender and health.

#### Garment Pressure

Any garment can be uncomfortable as a result of body movement if the friction against the body is high, thus preventing garment slippage, or if the pressure applied to the body is high when the garment is stretched around a curved body surface. For clothing, foundation garments generally exert the highest body pressures (Denton, 1971).

A system developed at the Natick laboratory to indicate relative magnitudes of pressure exerted by objects in contact with test subjects in static and dynamic positions, has been successfully used to improve the design of various Army gear. Body armor, helmets, restraint systems, and related items evaluated using this system were altered in design to relieve or redistribute forces. Use of this system resulted in 100% troop satisfaction of the improved items with regard to fit, comfort, sizing and compatibility with other equipment. Researchers at the Natick lab also used the system to develop lightweight, comfortable, inconspicuous body armor garments for law enforcement personnel (Barron, 1975).

Lemmens (1966) reported data on the range of pressures exerted on the body by different types of garments exercising some figure control (foundation garments and others). Swimwear pressure varied from .14 to .24 psi while foundation garments (girdle type) varied from .24 to .36 psi.

A garment pressure study was conducted at the Natick laboratory on ten subjects with a bra cup size of B or larger. Each subject wore her own bra for data collection. By placing a transducer at random points on the upper torso, five points were found to be the highest pressure points on all subjects. In Table 1 the number next to each point

Table 1

Average Pressure Loads for Torso Points as Measured by  
Costantakos in Nursing Bra Research

1. At the top of the shoulder- trapezius muscle: .94 psi.
2. Under the elastic band at the base of the bra, directly inferior to the nipple: .92 psi.
3. Under the top elastic of each side panel, directly inferior to the center of the armpit: .89 psi.
4. Approximately 1.5"-2.0" away from each side of the back clasp, directly inferior to the crest to the shoulder blade: .87 psi.
5. Directly inferior to the center of the armpit, in the middle of each side panel: .81 psi.

Note: Costantakos (1981) measured at all five locations and this study measured only at points 1, 2 and 4.

represents the average of pressures measured (Costantakos, 1981) for these five points.

Chambers and Moulton (1969) have investigated figure types and the fashions and fabrics which are appropriate for them. Their report on large busted women states that physical comfort may be obtained through a brassiere which provides support. The support is essential to protect delicate tissues in the breast. The support and control in a brassiere is achieved through design and fabrication.

#### Transducers for Measuring Garment Pressure

A transducer is "a device that converts one physical quantity (such as force, temperature, flow or displacement) into another physical quantity with more usable output characteristics" (Lyons, 1980, p. 147). A transducer may be used in the measurement of pressure. Pressure sensitivity is "the smallest pressure change to which the unit will exhibit a measurable response, expressed in a percentage of rated pressure range" (Lyons, 1980, p.198). The level of sensitivity required by the transducer is dependent on the type and magnitude of force measured. There are a number of systems that are capable of measuring different load levels on the human body, but none has been widely accepted.

Weinstein measured pressure sensitivity using a set of modified von Frey type filaments, consisting of nylon monofilaments calibrated on a chemical balance for the force

exerted. The filaments can be calibrated on a fine balance, and the force needed to bend them is measured in milligrams. It is assumed that the same amount of force will be exerted when these filaments are pressed onto the skin until they bend as when these filaments are pressed on the balance (Verrillo, 1975). The sensitivity stimulated not only varies with the strength of the mechanical stimulus applied, but also with the region of the skin stimulated.

The Load Profile Analyzer (LPA) system was developed by scientists at the Natick lab to measure and analyze characteristics of loads induced by objects in contact with a test subject in static and dynamic positions (Barrons, 1975). The LPA system incorporated a cloth garment (vest) that had a series of miniature transducers strategically placed to measure pressure. All transducers were joined into a single cable that connected the vest to a display panel. When pressure was placed on the garment, and a transducer compressed, contact took place between two components inside the transducer and an electrical circuit was completed. Load magnitudes and distribution of forces as transmitted to the torso of the test subject were indicated on a three-dimensional representation of an anatomical mannequin on the display panel. The display lights were designed to vary with the strength of the

mechanical stimulus applied, and also with the region of the skin stimulated.

The LPA system would not be useful in this study. The transducers were calibrated at 0.5, 1.0, 1.5 pound intervals. As demonstrated in Costantakos' (1981) research, pressure resolution in the 0.1 psi range is necessary to determine the data measurements between garments and the body.

The Entran EPF-200 is a system based on a semi-conductor bridge concept (Ames, 1978). Compression of a diaphragm above the semi-conductor causes the conductive properties of the material to change. A signal is generated and passes through a thermal compensating bridge. Advantages of the Entran include its thinness (0.040 in.) and small area (0.2 x 0.4 in.). It is also unaffected by thermal and environmental variations within normal human ranges. However, test results indicate that the transducer is not reliable because performance is dependent on how and where a load is placed. Another disadvantage is the cost, about \$250.00 per transducer, which is prohibitive to many projects (Ames, 1978).

Stephens (1983) studied garment wrinkle analysis as related to pressures applied to the body. A cube shaped Plexiglas strain gauge was developed and used to convert the energy of tension and stress on the body (a non-

electrical quantity) into a related electrical signal (a meaningful numerical quantity). The load-cell system consisted of two parts: the mechanical load-cell and the connecting bridge circuit. The strain gauges provided a measurable electrical output proportional to the stress applied by the load-cell. As the load-cell changed, the electrical resistance of the strain gauge also changed. Ten test garments made of lightweight unbleached muslin and consisting of a basic bodice with straight full sleeves were worn in the study by a single subject. Wrinkle analyses and pressure analyses were investigated for the areas in which wrinkles occurred on the test garments. The garment was donned and a body position was assumed that placed the back and shoulder area under maximum stress. The pressure of the garments against various areas of the back were measured. The purpose of this study was to test the method rather than to quantify pressure.

Fiber optics have been used to measure small pressures in bio-medical research. The high performance level and the minimal size encourage their investigation, but the cost of related equipment currently prohibits its widespread use (Ames, 1978).

Strohman and Tomarazzo (1977) developed a load sensing system using a material, Dynacon C, that exhibited conductivity as a function of pressure. The material

consisted of a conductive substance imbedded in an elastomeric material. The Dynacon advantages were many, including low cost, ease of forming or molding and specific pounds per square inch readouts. However, the Dynacon material could not distinguish between compression and shear pressure when collecting data and it was recommended that a material more sensitive to compression be used in further research. Also Dynacon deteriorated with age and use. Finally, there was a loss of accuracy in readings due to thermal effects and hysteresis (the inflation pressures do not equal the deflation pressures). The accuracy of the readings was also influenced by the inability to manufacture a uniform product. Costantakos (1981) used Dynacon C in her pressure analysis of the nursing brassiere because no more sensitive material was available at the time. Dynacon is no longer available.

The Natick lab has developed several pneumatic bladders with electrical contacts for detecting load thresholds (Barron, 1974). Disadvantages of this system include cumbersome and bulky electrical and pneumatic connection for the bladders and inaccurate readings due to the pinching of the air tubes. In addition, all transducers were connected to a common air source, and different loads could not be detected simultaneously (Barron, 1974).

The operating principle of a pneumatic bladder transducer differs from that of other transducers. Transducers such as the Dynacon and other pliable, compressible electrically conducting materials attempt to convert forces (pressures) to a measurement of electrical resistance. The behavior of such transducers may depend on the rigidity of the support material. To characterize the reaction of any compressible body, as in the case of the Dynacon transducer, Hooke's law applies. An example using coil springs will illustrate Hooke's law. In Figure 1a a spring is compressed a distance  $x$  by applying force  $F$ . Hooke's law states  $F = kx$ . The compressibility of the body, the spring in Figure 1a, is denoted by the spring constant  $k$ . In Costantakos (1981) research the compressible body is the Dynacon transducer. Calibration of the transducer is done to determine the value of  $k$ . Hooke's law as stated does not allow for nonlinear behavior but a calibration graph does not depend on linearity.

Figure 1b illustrates the case of two springs, or compressible bodies, in series. Spring 1 is the Dynacon and spring 2 is the support, either a rigid body like a table top for calibration or the skin and underlying tissues when the transducer is in use. When the same force  $F$  is applied to the two springs Hooke's law states:

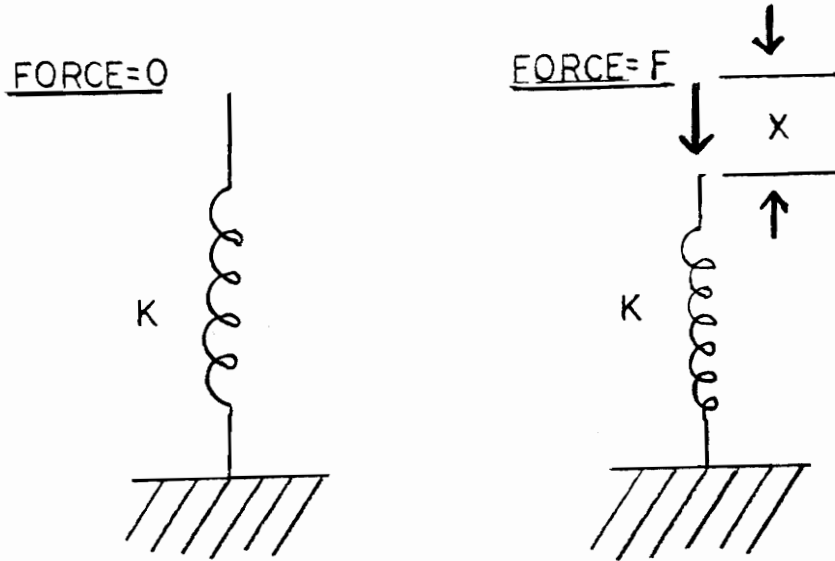


Figure 1a

Hooke's law describes the compression of a spring due to an applied force. On the left side of Figure 1a the spring has no force ( $F=0$ ) applied as it is not compressed. As shown on the right side of the figure, the application of a force ( $F \neq 0$ ) compresses the spring by  $x$ . The spring is characterized by the spring constant  $k$ :  $F=kx$ .

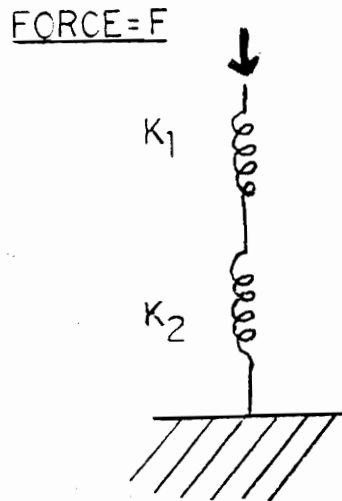


Figure 1b

Hooke's law applies to two springs in series. This system can be described by an effective spring constant, which is calculated from this individual spring constant, as shown in the text.

$x_1$ , compression of spring 1 =  $F/k_1$  and

$x_2$ , compression of spring 2 =  $F/k_2$ .

To denote the total compression by  $x$  then

$$\frac{F}{k_1} + \frac{F}{k_2} = x.$$

Simplifying this

$$F \left( \frac{1}{k_1} + \frac{1}{k_2} \right) = F \left( \frac{k_2 + k_1}{k_1 k_2} \right) = x$$

$$F = \left( \frac{k_1 k_2}{k_1 + k_2} \right) x$$

Two special cases exist.

Case 1

$$k_1 \gg k_2, \text{ then } F = \left( \frac{k_1 k_2}{k_1} \right) x = k_2 x.$$

Case 2

$$k_2 \gg k_1, \text{ then } F = \left( \frac{k_1 k_2}{k_2} \right) x = k_1 x.$$

If  $k_2$  describes a transducer that depends on compression and calibration, then case 1 would be the situation if the transducer were on a table top and the compressibility of the table top is given by  $k_1$ , i.e., the table top does not compress except under very high force. In that case then

the spring constant and the compression that are being measured are those of the transducer.

Case 2 is the situation of a transducer being supported by a surface that is very compressible as compared to the transducer, such as the skin and underlying tissues. In this case the effective spring constant is that of the skin and underlying tissues, not the transducer. An example of this is using a bathroom scale on a padded rug. The scale will always underweigh because part of the force is compressing the rug and not the spring in the scales.

For a pneumatic bladder transducer, the skin or underlying support surface is compressed by a force which is then equilibrated by the inflation of the transducer. Little or no additional compression of the skin should occur during the inflation of the transducer, i.e. the surface is relatively incompressible and case 1 would exist. The force measured would be the actual force of the garment.

### Summary

Methods are needed for quantifying garment fit by measuring pressure of garments against the skin. In order to develop this type of objective measure of garment fit, a low cost device must be developed which can give reliable and valid measures of garment pressure.

## Chapter III

### METHODOLOGY

The purpose of this study was to develop and test a transducer to measure the perpendicular pressure between a garment (brassiere) and the underlying skin of the shoulders, breast and back. A pneumatic bladder type transducer was developed and connected to a system which assisted in data collection. The transducers were calibrated and used with a human subject wearing a test brassiere.

Various types and magnitudes of forces are exerted by a garment on the body. Because there are a wide variety of garments, a wide range of forces and pressures need to be considered. When choosing a transducer one must consider the end use and the resolution of the transducer (range at which the transducer collects data).

#### Test Apparatus

The pneumatic bladder type transducer does not attempt to measure pressure, since an accurate air pressure source serves that function. The transducer detects when the air source has balanced the load of the garment. In other words, when the pressure inside the bladder is higher than the pressure outside, the contact points will open. Once the electrodes release the pressure is recorded. At the

point of release, the air pressure equals the load from the garment.

The transducer, one of the main elements in the apparatus, is the device developed in this research. Other significant parts include the air chamber, the analog to digital (A/D) converter, and the personal computer (Figure 2). A power supply connected to each transducer (T1, T3, T4) provided electrical voltage. Resistors (R) were used to limit current flow out of the battery to eliminate short circuiting the power supply. The apparatus had to be sensitive to compression caused by pressure exerted by a garment. As the amount of externally applied pressure increases, the amount of air pressure necessary to open the electrical contact in the transducer must increase. The contact opens and closes as the air pressure changes in conjunction with the pressure exerted by the garment and the body.

The transducer attributes include the following: it is inexpensive to make, it is flexible and disposable, and only one air source is needed for detecting multiple transducers and corresponding pressures.

#### Transducer Development

Through experimentation with a variety of different components the final materials for the apparatus were

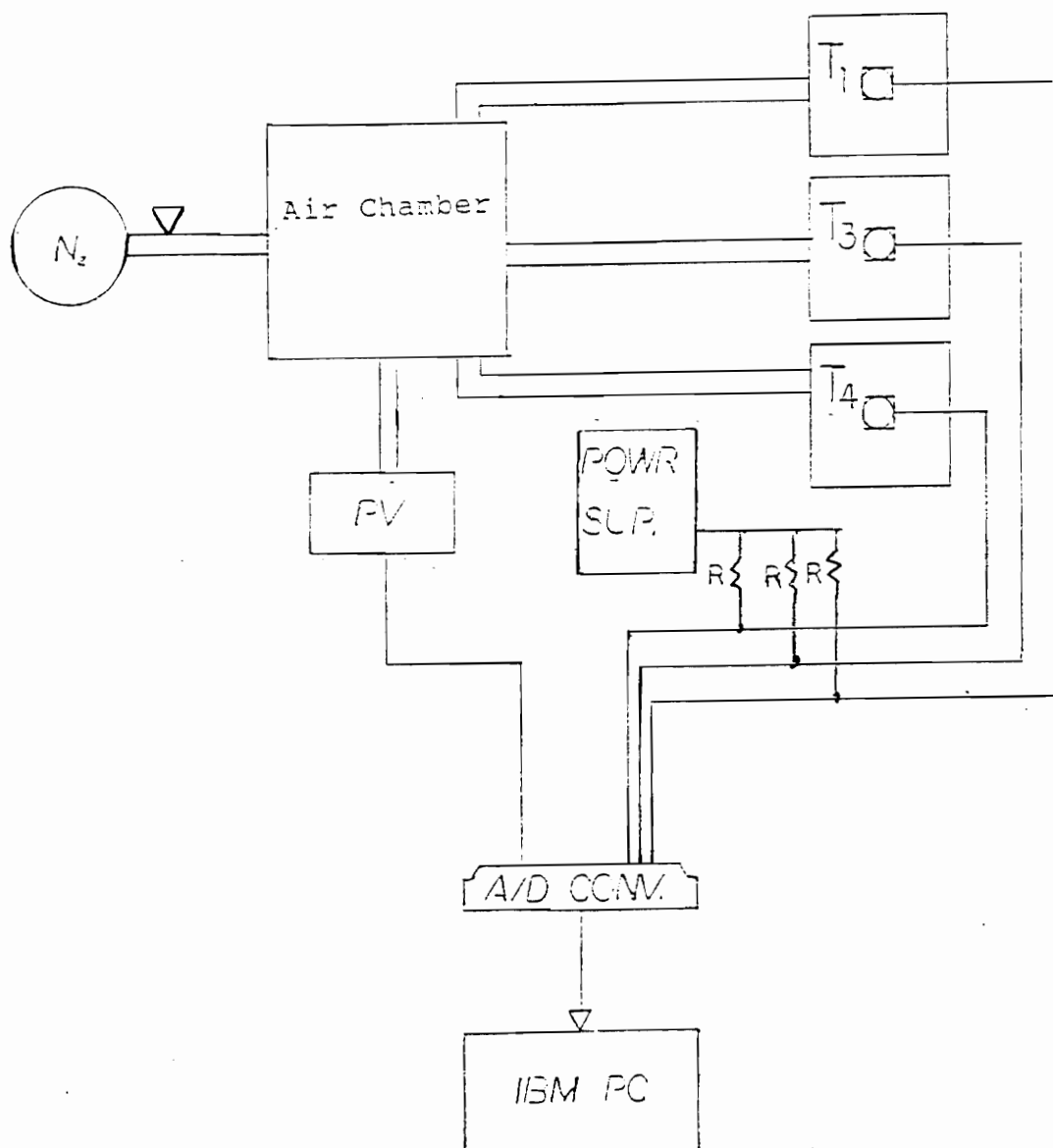


Figure 2

Diagram of transducer apparatus

Note: An air pressure source,  $N_2$ , is connected to the transducers (T1, T3, T4) through an air chamber. The pressure in the air chamber, and thus the transducer, is adjusted by the pressure valve, PV, which is controlled by the PC. A power supply is connected to each transducer through current limiting resistors, R. The A/D converter is connected to each transducer to allow the PC to monitor if a given transducer has opened or closed contacts.

selected. The transducer was constructed of materials which may be purchased at hardware and fabric stores.

The bladder material had to be a substance that was durable, flexible and could be sealed airtight. Materials considered for the bladder included several varieties of plastic bags (food storage types) and different weights of vinyl. The product chosen for the bladder was a thin, 0.007-in. vinyl purchased at a fabric store (\$4.39 per yard-1/4 yard purchased). The vinyl was cut into 2 x 3 in. strips and folded in half to make a rectangular bladder. The center of each 2 X 1.5 in. section of vinyl was buffed lightly with sandpaper to ready the surface for electrode placement.

The contact points had to be a conductive material that was also flexible. Each contact point would be attached to a wire, which leads to the computer, and affixed to the vinyl to make the electrode. One-quarter inch squares of .002 inch thick copper shim (\$5.66 per sheet) served the purpose. The shim was more durable than the aluminum foil that was tried in early prototypes.

A flexible wire to transmit the electrical current from the transducer to the A/D converter was needed. It also had to be thin in order to fit through the small diameter tubing being used. An insulated wire (\$2.79 per 50-ft. roll) was necessary to eliminate electrical contact anywhere but

inside the transducer bladder. Approximately one-eighth inch of the wire was stripped of the insulation and the tip was soldered to the center of the contact point forming the electrode. The wire was twisted into an "S" shape between the electrode and the end of the tube so as not to cause tension upon inflation.

The air tube, leading from the transducer to the central air chamber, needed to have the smallest diameter possible to encase the two wires and yet allow air passage. A small tube would be less bulky and cumbersome. A very flexible Tygone Fisher 0-073 ID tubing (supplied by the Agriculture Engineering Department at Virginia Tech) was used at the mouth of the bladder because it bonded with the adhesive used to seal the bladder. Due to the difficulty in passing the wire through this tube, only a six-inch length was used. The additional tubing that connected the Tygone tubing to the air supply needed to be flexible but not pinch or crease easily. A one-sixteenth inch diameter Teflon tubing (supplied by the Agricultural Engineering Department at Virginia Tech) was selected as the wires slipped easily through the length of the tube. The two tubes were butted together and wrapped with electrical tape to make an airtight connection. Similar tubing may be purchased for .14 cents per foot (total .56 cents) and .16 cents per foot (total \$4.80) respectively, at a hardware store.

The substance used to bond the electrode to the vinyl was Scotch<sup>TM</sup> Brand double stick tape (\$1.29 per roll). It was cut slightly smaller than 1/4 in. squares and attached to each electrode. Each electrode was then pressed firmly to the inside face of the vinyl. The electrode position was centered on each side of the folded vinyl piece that was buffed. A liquid adhesive could not be used because it interfered with the contact as the electrode became submerged in the adhesive.

The adhesive chosen to seal the bladder was a solvent cement. It is the type of substance used to patch a hole in a waterbed (\$2.95 per kit). A 1/4 in. seal was formed around three sides providing an active transducer space of about 1.25 in. square. Weights were placed on the seams in an attempt to keep them flat while they cured. After curing, the edges were slightly rippled and stiff. The transducers were not completely flat but the electrodes made contact in the deflated mode. (Figure 3)

#### Data Recording

A set of equipment compatible with a personal computer was developed to simplify data collection and interpretation. A computer program, which converts an electrical impulse into digitizing units transformable into psi pressure units, was used to monitor the air pressure and electrical continuity of the transducer. The A/D converter

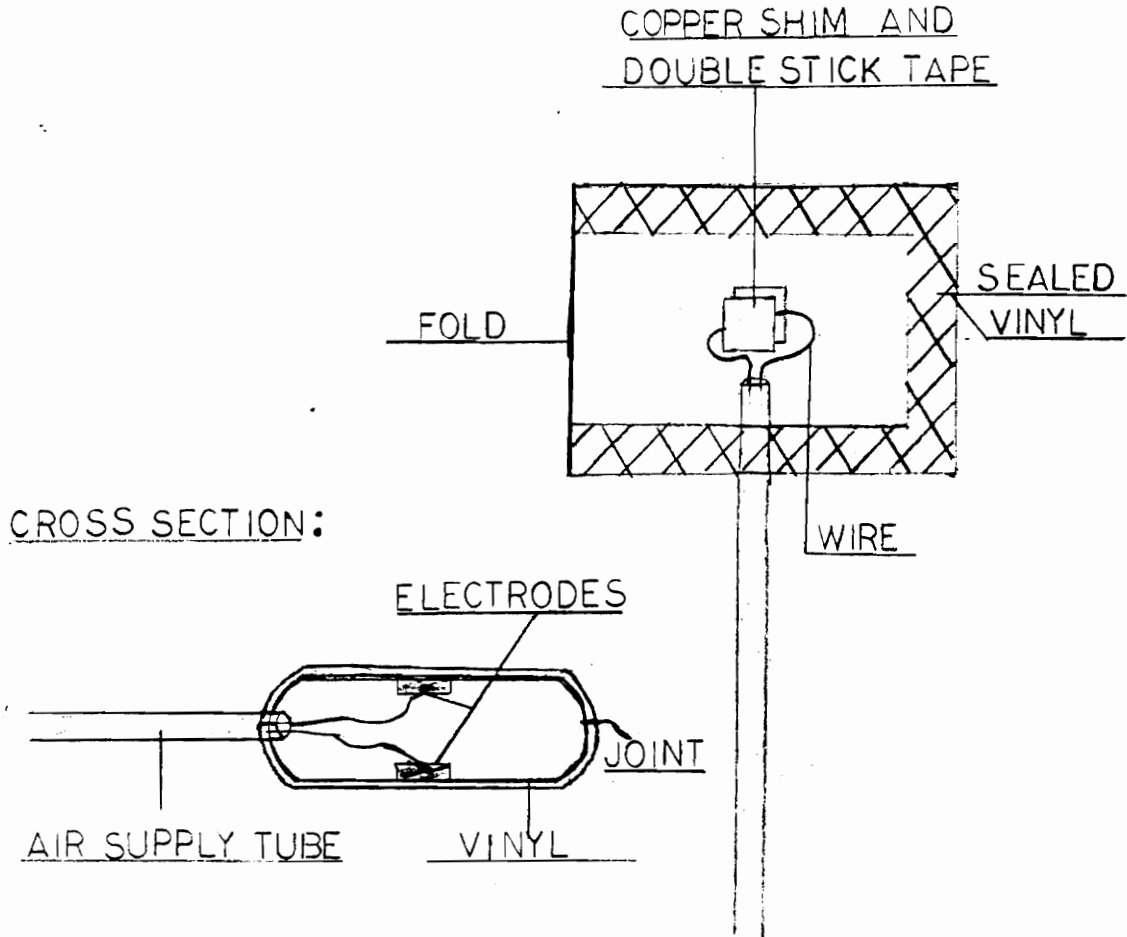


Figure 3

Transducer Diagram

Note: The transducer is a sealed, vinyl envelope connected to an air supply. Inside the envelope two electrical contacts are adhered to opposite faces. As the air pressure inside the transducer is increased, the electrical contacts open as the vinyl expands. The PC monitors the contacts to detect their opening and closing. When the contacts open the air pressure inside the transducer equals the external pressure applied by a garment or calibration weight.

transformed approximately 20 readings per second of air pressure and electrical continuity saving the first ten readings for each inflation and deflation cycle for each transducer. This provided the option of single or simultaneous transducer readings.

The air pressure and electrical continuity were measured as shown in the flow chart in Figure 4. The measurement cycle began by setting the air pressure to approximately zero psi, then sending a command to the air pressure controller to start slowly raising the air pressure. As the pressure rose, the computer program read the A/D at twenty readings per second, until it detected that the switch had opened. Once the opening of the switch was detected the program read the value of the air pressure ten times, sent a command to the air pressure controller to shut off the air, then stored the air pressure readings in a data file for subsequent analysis. Therefore, for any given application of load ten readings were averaged to determine the pressure reading.

#### Calibrating the Transducer

The method for calibrating the transducer required a balance and accurate weights to furnish given pressures. Each transducer was checked to determine the amount of air pressure necessary to relieve contact between the electrodes when the transducer was loaded with weights that created

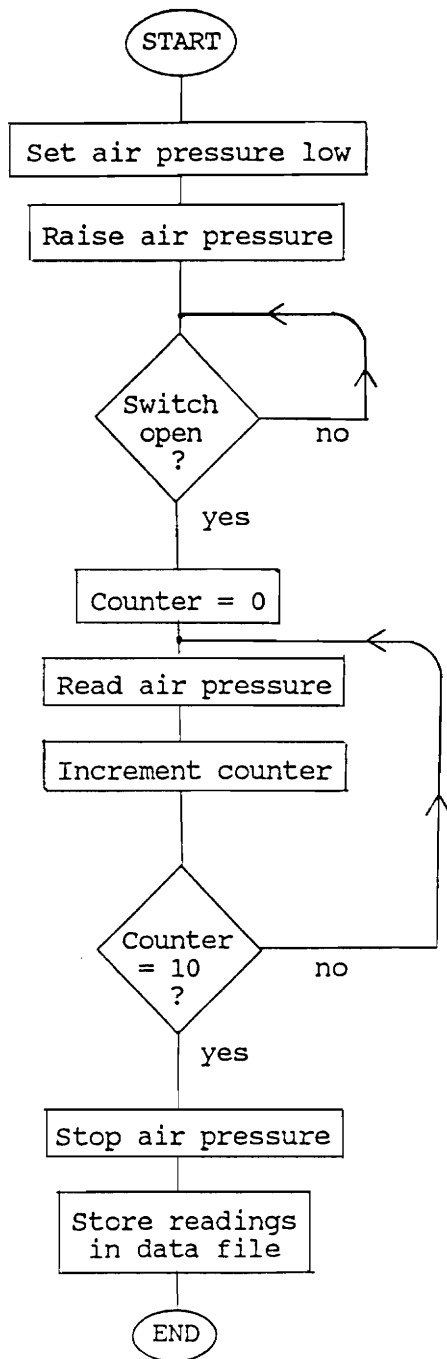


Figure 4

Air pressure and electrical continuity flow chart

predetermined levels of pressure on the transducer. The weights were applied to a 1/4 in. diameter jig base and centered on the transducer electrodes. The transducer was inflated to the pressure necessary to equal the applied calibrated pressure as determined by the opening and closing of the electrodes. The active area of the transducer is approximately 1.6 square in. The 37 grams applied over an area of 1/4 in. diameter is .05 psi. An ideal transducer acting like a piston would have the ratios of the areas .05 square in. versus 1.6 square in. should scale as .18 psi versus 1.7 psi. The difference arrives because the geometric area is not the effective open area of the transducer. One means of measuring the effective area would be to ratio 1.7 versus .18 and multiple by .05 (1/4 in. jig base area). The description is equivalent to the operating principle of a hydrolic press or hydrolic jack (Schaum, 1962). The calibration results help determine the linear response and repeatability of the transducer.

Each transducer was calibrated individually. In addition to this, inflation and deflation modes were calibrated separately for a transducer. This was done to determine if the transducers exhibited hysteresis.

The weights used for calibration and the resulting pressures were: light weight = 37 grams/1.70 psi; medium

weight = 67 grams/3.07 psi; and heavy weight = 150 grams/6.89 psi.

The pressure characterization of the transducer was determined in the calibration stage. The pressure response of the transducer was analyzed to test the linear response of each transducer as well as the repeatability of the measurements. A test of the reproducibility from transducer to transducer was also conducted. The data collected were examined to reveal the number of transducers with the same pressure response.

The reliability of the instrument deals with the accuracy and precision of the intended measurement. The instrument accuracy was demonstrated through calibration with standardized weights. The repeatability of the instrument was determined by test and retest method using the same standardized weights. For each transducer three applications per weight, a total of nine readings per transducer, were collected.

The complete sensing apparatus, balance unit and calibrated weights were used in the calibration test for an accuracy measure. The elements monitored during testing were the air pressure, the calibrated weight applied and the electrode contact.

The transducer was placed on a solid surface and the balance unit was applied to the center of the transducer.

The calibrated weights were added to the balance and the bladder was inflated and deflated. The amount of pressure required to open and close the contact points was recorded by the computer program in digitizing units.

#### Human Subject Pretest

The pressure measured in this study was the distributed force upon specified locations of the upper torso caused by the weight of the breasts as supported by a test brassiere. The pressure was measured using the transducer and accompanying apparatus developed in this study.

The test was conducted in the Mechanical Engineering Laboratory at Virginia Tech. A human subject was seated during data collection. A mannequin was not used in the research as no mechanical or non-living model has been devised to simulate the interactions between clothing and the body (Fourt and Hollies, 1970). The data were collected from the right side of the body, following customary anthropometric techniques (Anthropometric Source Book, 1978). The subject was seated in an upright position with shoulders back in a relaxed, comfortable posture for data collection.

Selection of a bra for the study was based on style popularity as indicated by sales data, manufacturer claims, and availability. Only those bras that sold 50 units or more in a six-month period were considered. The Playtex<sup>TM</sup>

bra style 27 was the top seller at a local department store (Table 2). The Playtex<sup>TM</sup> bra style 27 is advertised as a well-fitting bra. The "cups are suspended in a unique self-adjusting frame of sheer lightweight elastic for freedom of movement and customized fit" (International Playtex, Inc., 1986). See Table 3 for complete bra description.

A subject was selected using the following criteria.

1. Bra size 34D.
2. Bra fits according to check points for proper fit indicated in the Playtex<sup>TM</sup> Fitting Guide.

a. Each bra cup should fully contain the breast.

Bulges at the top of the side indicate that the cup is too small. If the cup is not completely filled, wrinkles will appear showing the bra cup is too large.

b. The bra band should be snug but not tight around the rib cage. Binding may indicate that the back size is too small or that the back closure of the bra is fastened too tightly.

c. The back of the bra should be straight across the back. If it rides up, the bra size may be too large, the bra may be hooked too loosely, or the straps may be adjusted too tightly.

d. The center front of the bra should lie flat against the breast-bone. If it bridges away from the body, the cup size is too small.

Table 2

Bras which sold 50 units or more in a six-month period

	Style Number	Units Sold
Playtex <sup>TM</sup>	27	170
	42	108
	807	93
WOW <sup>TM</sup>	950	74
	628	82
Bali <sup>TM</sup>	3820	67
	180	166

Note: Data provided and compiled by local department store.

## Table 3

Bra description for 18 Hour Playtex bra style #27, 34DContent

- 100% polyester cup facing
- 100% cotton cup and band lining
- Elastic: Frame; nylon DuPont spandex  
Back and band; rubber, nylon

Fastening Systems

- 4-hook back
- Adjustable elastic straps
- Zig-zag stitching on elastic
- Straight stitching on all other parts

Structure

- Two semi-circles seamed horizontally to form cup
- Lace edge trim around cup
- Cups supported underneath by rubber and nylon panel which is stabilized with woven cotton fabric
- Cup is enclosed on all other sides with spandex panels
- All structural seams inside bra cup are stabilized with 1/4" bias tape
- Back is structured with two pieces of spandex fabric that graduates from 3" at center back to 5" at side seam
- Elastic band 3/4" lower edge
- Elastic trim 3/8" top edge of bra
- Elastic strap 7/8" from center back to highest point on cup

e. The straps should be adjusted to support comfortably without binding.

Costantakos (1981) isolated five critical pressure points for this type of garment (Table 1, pg 10). Time constraints prohibited the testing of five transducers at five pressure points. Thus three of the five transducers were randomly chosen for use in the pretest data collection and the three highest pressure points found by Costantakos were selected. However, no reading was obtained using the side panel point, so readings were taken using the fourth highest pressure. The three body points that were used for data collection were: under the strap at the top of the shoulder; under the elastic band at the base of the bra, directly inferior to the nipple; and under the bra about 1.5-2.0 in. away from each side of the back clasp, directly inferior to the crest of shoulder blade.

Three of the six transducers were tested to illustrate the sampling adequacy of the apparatus. The transducers were placed one at a time at each of the three locations for data collection.

#### Data Analysis

The analysis of the data was accomplished with the use of a computer program that read data files created during the calibration phase and computed mean and standard deviation for calibrated pressures. A second program used

Students t-tests to check test transducer to transducer variation during calibration and test, variance of inflation and deflation, and variation from weight to weight for each transducer studied.

The questions to be answered by this study are:

1. Did each transducer accurately differentiate between light, medium and heavy weights?
2. Did each transducer provide a linear response?
3. For a given transducer how repeatable is a measurement?
4. Was there variation transducer to transducer?
5. Can the transducer be used with a large busted human subject wearing a brassiere?

## Chapter IV

### RESULTS

Based on the procedure described and using the selected materials mentioned, six transducers were made (T1-T6). The methods of assembly were acceptable for this study. T2 developed a leak early in the calibration stage and was eliminated from analysis.

The transducers were calibrated individually. The calibration range was 0.2 to 0.5 psi with a resolution of .02 psi.

The cost of materials was \$19.15 (includes pricing for all materials). There were materials left over after the assembly process. The average cost per transducer was less than \$3.19.

#### Findings

Students t-test was conducted for each transducer to determine the ability of each transducer to differentiate between the light (37g/1.70 psi) and medium weight (67g/ 3.07 psi) and medium and heavy (150g/6.89 psi) weights. Three replications of a given mass were applied for each transducer. The distinction between light and medium weight for transducers T1, T3, T4 and T5 were significant at  $p < 0.01$  and for transducer T6 was significant at  $p < 0.1$ . A .01 significance was found for all five transducers for the medium to heavy weight distinction (Table 4).

Table 4

T-test data for differentiating applied weight to transducers for inflation mode of calibration stage

Applied Weights	T1	T3	T4	T5	T6
37g to 67g	p<<0.01	0.01	0.01	0.01	0.10*
67g to 150g	p<<0.01	0.01	0.01	0.01	0.01

Note: The difference may be due to the rigidity of T6 or that the electrodes were sticking at the lower applied pressures.

If a transducer provides a linear response, a load that is doubled for a given transducer should take twice the pressure to open the switch if that transducer is linear. The inflation data plotted on the graphs in Figures 5, 7, 8 indicate that transducers T1, T4 and T5 gave linear responses. Transducers T3 and T6 depart from linearity (Figures 6, 9). Each departs on the low end of the scale indicating that something is causing it to deviate at the lower pressures. That deviation should not discount the reliability of the transducers since the origin was not included as a point of measure. However, each transducer does go very close to the origin. The offset of the line is small enough, 0.03 psi, to be considered non-meaningful.

The graphs in Figures 10-12 illustrate how repeatable a measurement is for a given transducer. The transducers have been paired using inflation and deflation numbers and separated by weight applied. As shown in the graphs, the inflation and deflation pressures are not equal and therefore, hysteresis is present. In all three calibration pressures, transducers T1, T4 and T5 show approximately the same average reading and same overlap in error bar. The transducers are not identical but each was individually calibrated.

Three transducers, T1, T4, and T6 were used to collect the data on the subject wearing the test brassiere. The

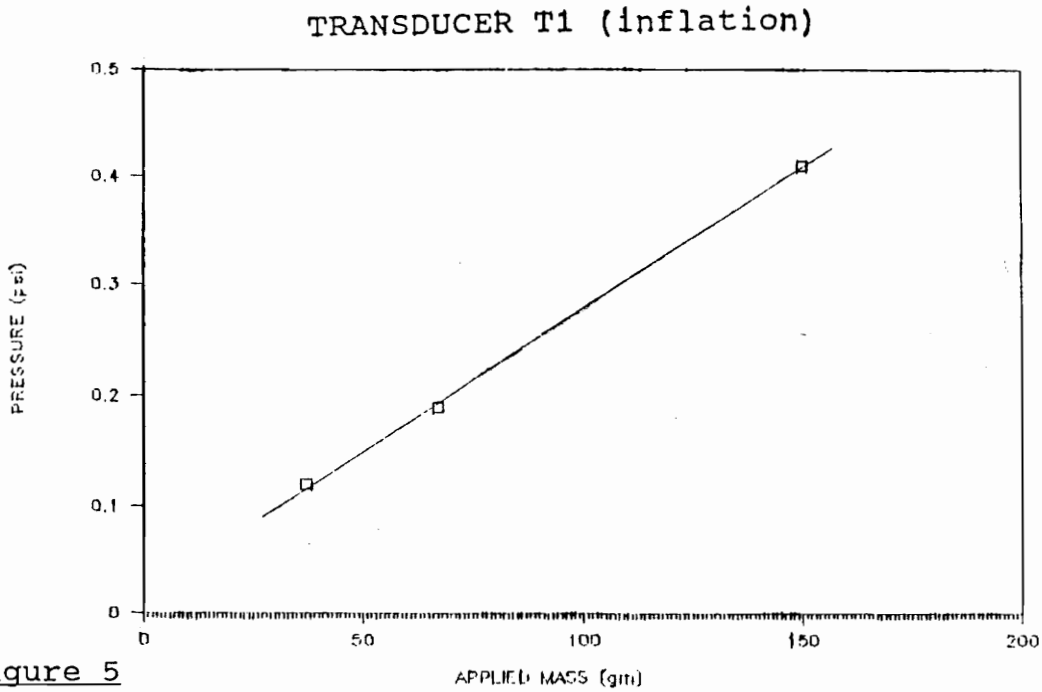


Figure 5

Average pressures for applied masses to T1 inflation mode

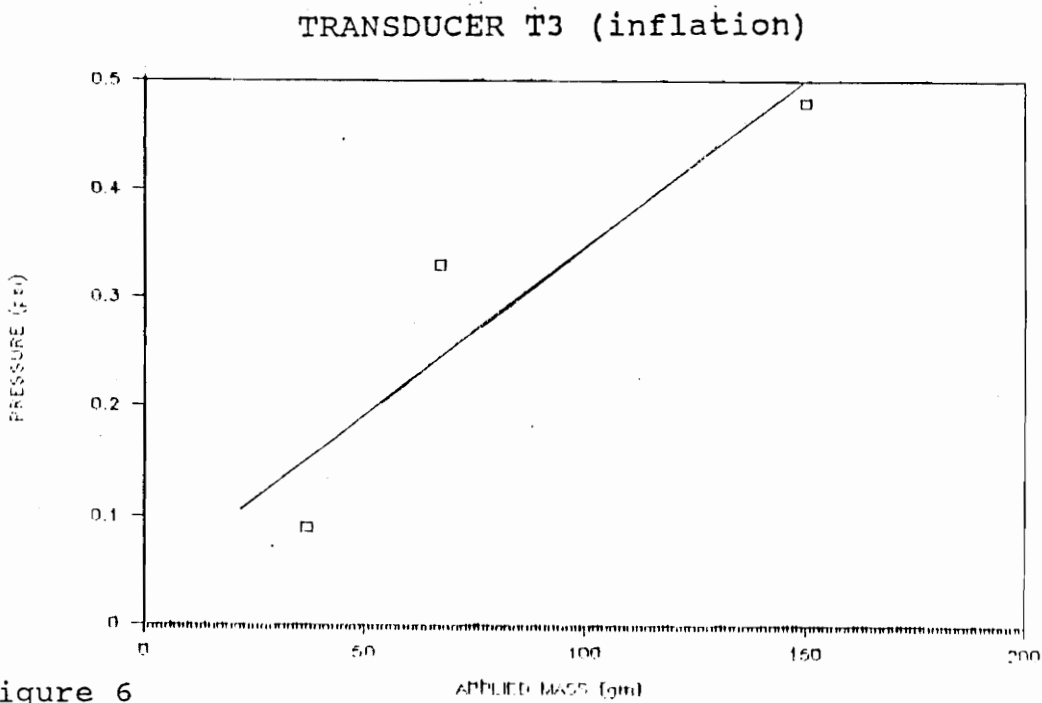
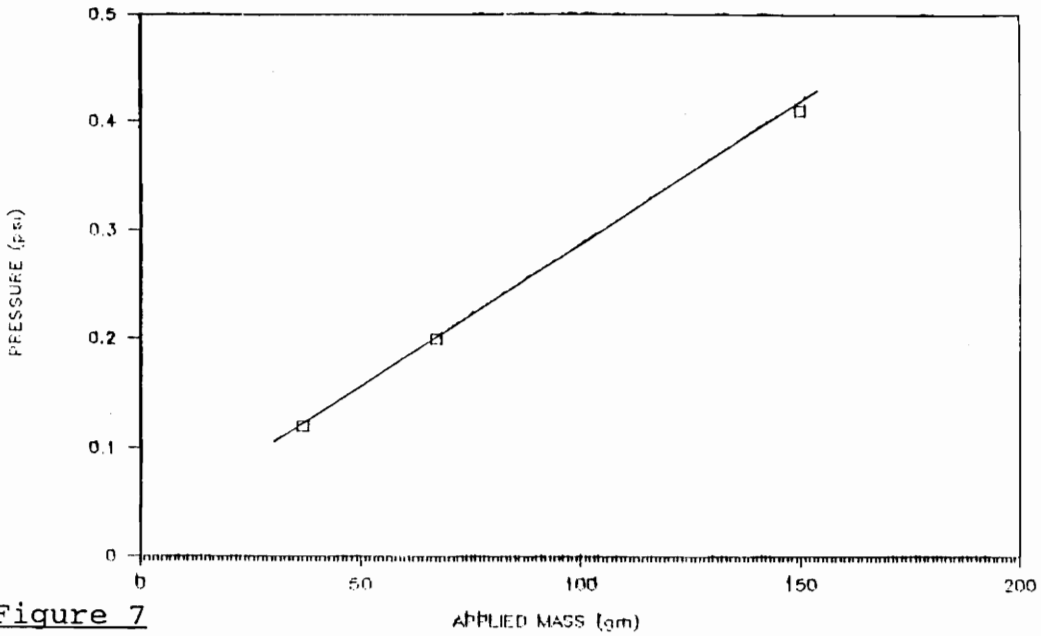


Figure 6

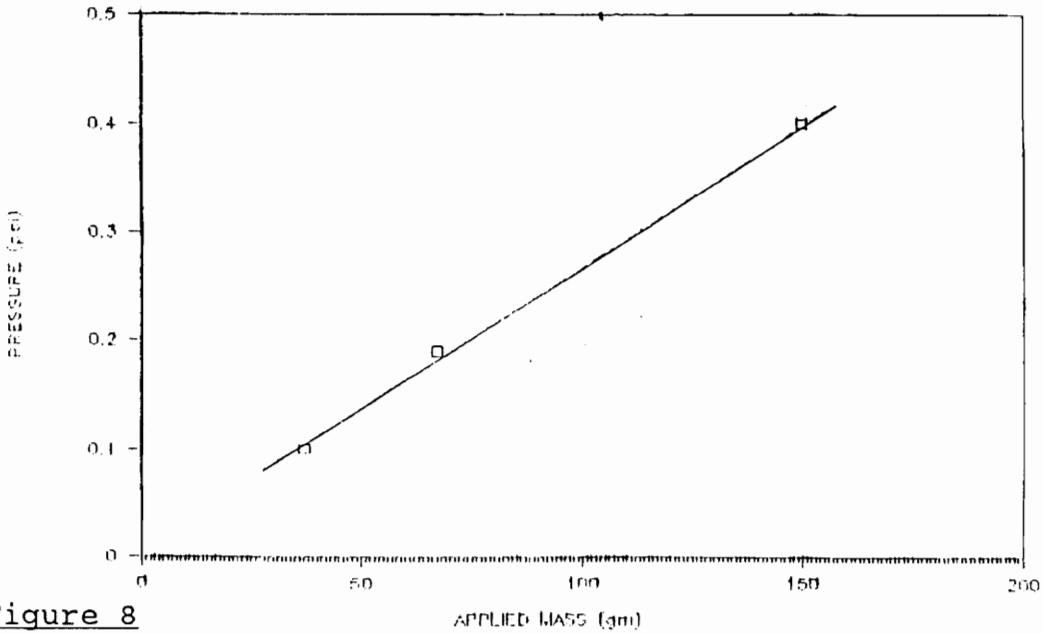
Average pressures for applied masses to T3 inflation mode

## TRANSDUCER T4 (inflation)

Figure 7

Average pressures for applied masses to T4 inflation mode

## TRANSDUCER T5 (inflation)

Figure 8

Average pressures for applied masses to T5 inflation mode

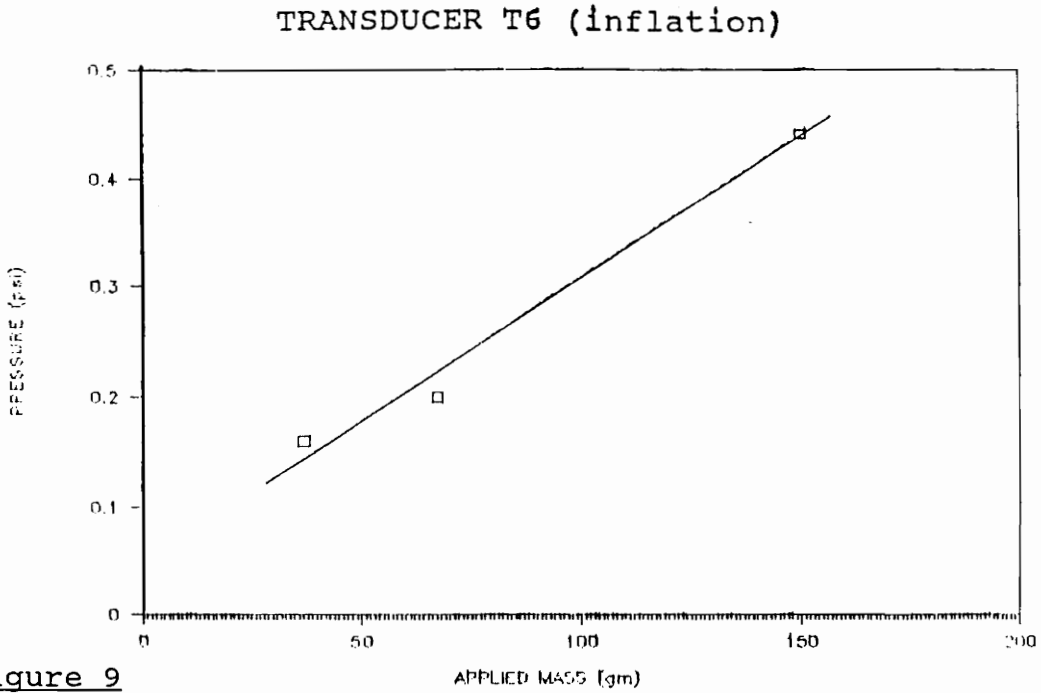


Figure 9

Average pressures for applied masses to T6 inflation mode

## LIGHT WEIGHT (37 gm)

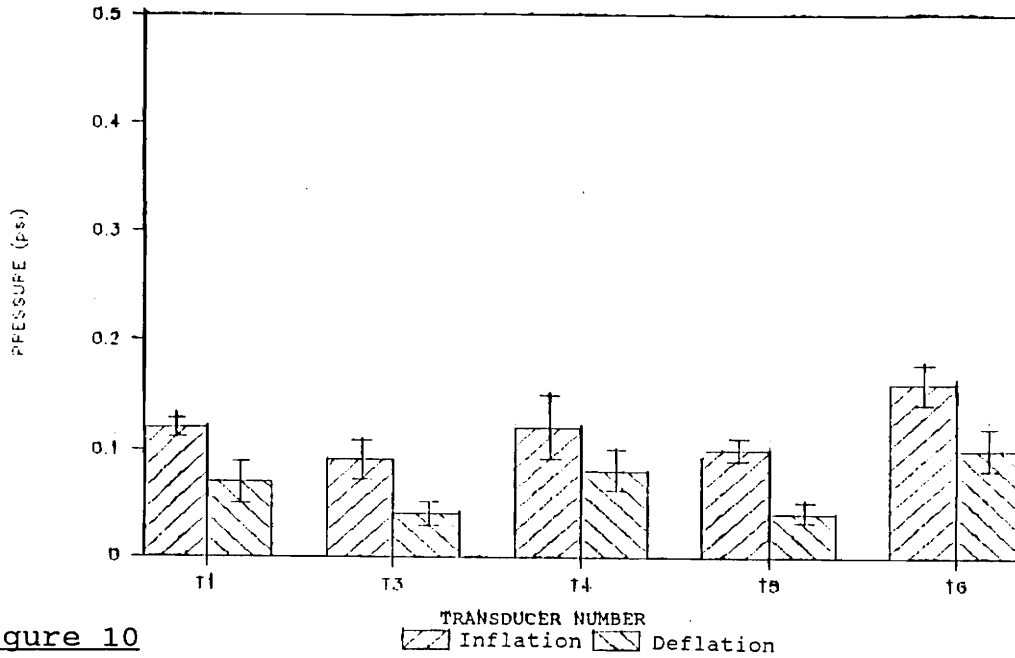


Figure 10

Transducer comparison for the average pressure for inflation and deflation mode using 37 gram weight

## MEDIUM WEIGHT (67 gm)

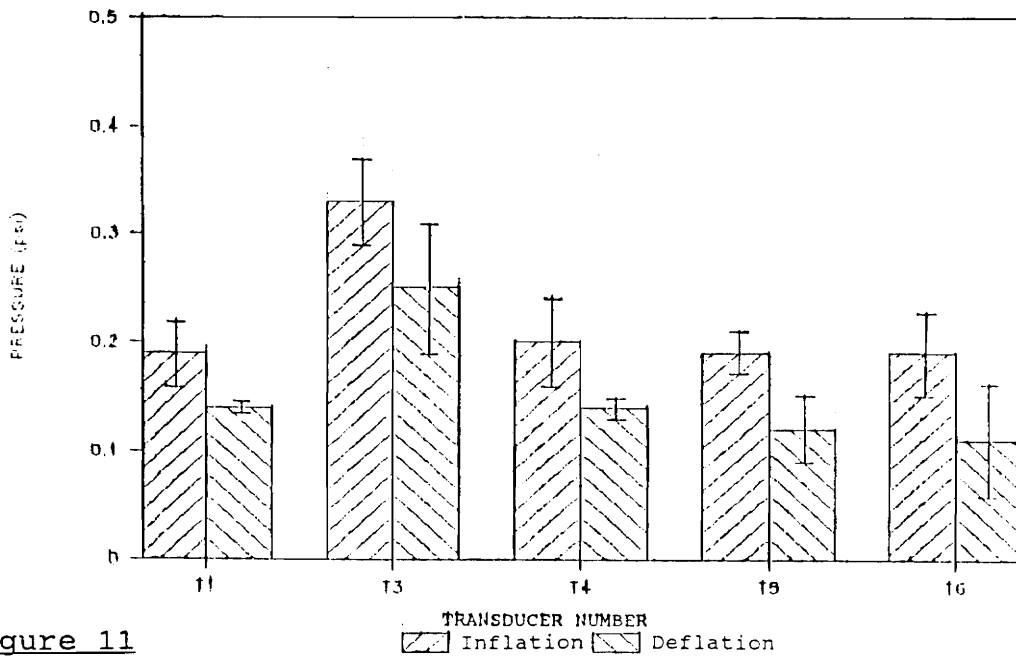


Figure 11

Transducer comparison for the average pressure for inflation and deflation mode using 67 gram weight

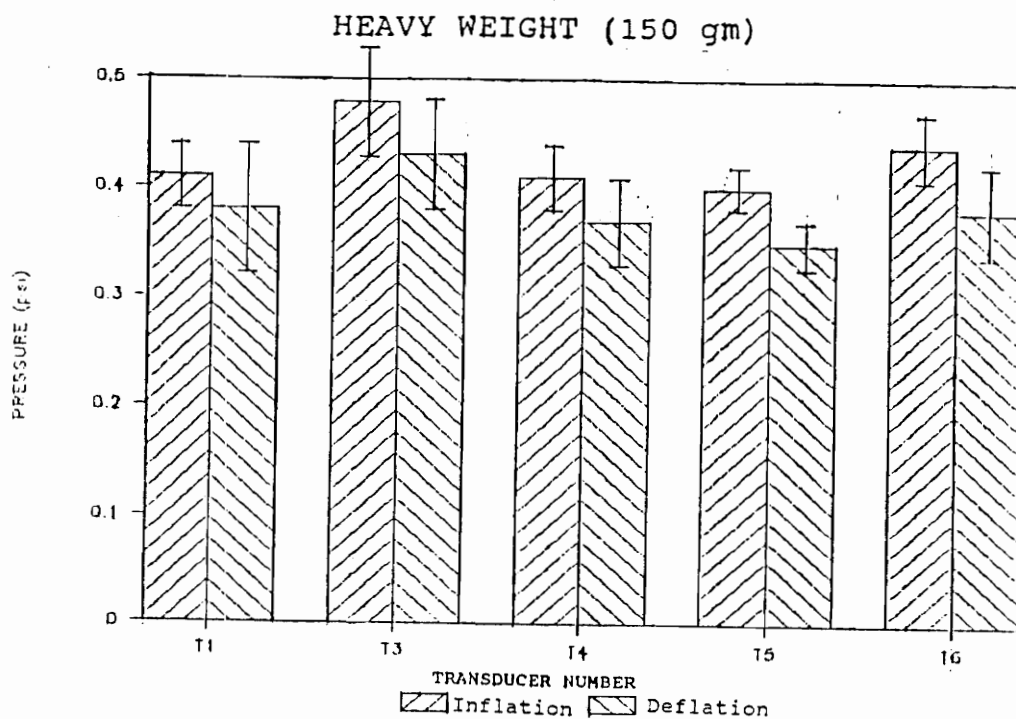


Figure 12

Transducer comparison for the average pressure for inflation and deflation mode using 150 gram weight

Note: A comparison of the pressure at which each transducer opened the electrical contacts on inflation and closed them on deflation. The difference in such pressure is the hysteresis of the transducer. Error bars are  $\pm$  one standard deviation.

matrix in Table 5 shows a transducer average for each measurement point. Three tests were conducted using each transducer. T6 has a very high average at the shoulder measurement point. Because this number is out of the range of T1 and T4 data it was ignored in the results. The average for the T1 transducer at the front bra position is much lower than T4 and T6, and was also eliminated from the average analysis in Table 5.

The averages for each measurement point for this research are different, they are lower, than those compared in the nursing bra study. Costantakos research demonstrated higher average pressures per subject. (See Table 1, p. 9) The numbers are different, but similar conclusions can be drawn for the weight distribution of the breast in the test brassiere. The highest pressure is on the shoulder point and the lowest pressure is on the back. Differences in the results of the two studies may be attributable to several factors. This study used a single subject rather than multiple subjects since the objective was to determine if the apparatus could be used successfully in a test using human and garment. The subject for this study was a large busted woman in her early 40's whose body may have made adjustments over her lifetime. Costantakos' subjects were lactating women who may not normally have been large busted. On the average, subjects in the nursing bra study were

Table 5

Average pressure readings for three replications per transducer at specified torso points

	Shoulder	Back	Front
T1	.31	.12	.15
T4	.28	.12	.23
T6	.44	.11	.25
Ave.	.30	.12	.24

wearing bra sizes larger than the individual in this study suggesting that they were larger overall.

Chapter V  
CONCLUSIONS

The purpose of this study was to develop and test a transducer to measure the perpendicular pressure between a garment (brassiere) and the underlying skin of the shoulders, breast and back. A transducer was developed, calibrated and tested using a human subject for data collection. Results indicated that the transducer provided a linear response and was a valid and reliable instrument for determining pressure in the calibration stage. Furthermore the apparatus was successfully used to measure the pressure between a garment and the underlying skin.

The transducer was made of inexpensive materials found at hardware and fabric stores. Some of the materials for this study were provided by the Agricultural Engineering Department at Virginia Tech. The cost of materials for six transducers, had they all been purchased, would have been about \$19.15. The apparatus was connected to a personal computer for data collection.

Suggestions For Further Research

Further development of the transducer may be considered for future research. Making the transducer more uniform in area and smaller would enhance the accuracy of data collection. The calibration process could be improved by covering the active area of the transducer with the load.

Less pressure is required to open the switch and balance the force if a small portion of the transducer is covered. Calibrating over a larger range (0-2 psi) would allow for data collection at higher pressure points on the body.

The research revealed that it is possible to develop an inexpensive transducer that is reliable for data collection. The ability to evaluate garments in an objective manner could be combined with the subjective analysis of a model wearing a test garment. Research could be conducted using a large busted woman wearing a garment such as a sports bra, a swimsuit or other exercise apparel, and pressure between the garment and the skin could be analyzed. The analysis could provide information for redesigning a garment that is both functional and comfortable.

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## Vita

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