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OBJECTIVE EVALUATION OF GARMENT PRESSURE

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14. ABSTRACT

Very sophisticated single-point and multi-point flexible pressure sensors were used to objectively evaluate the pressure applied by a garment on the wearer's body. Both commercially available civilian garments and prototypes for military garments developed by the Garment Team at the LEHP were used in this study. The objectives were (1) to establish a correlation between subjective evaluation of comfort and pressure values at various location in a garment, and (2) to extend this comparison of wearers' subjective perceptions and objective pressure values to prototypes of military garments developed by researchers at LEHP. The methods developed in this study can help researchers determine points of high pressure in a garment and areas requiring modification. The objective measurement methods used in this study can also help in comparing pressure comfort of many garments without going through time-consuming subjective evaluation. This study also confirmed other researchers' conclusions that objective measurements of garment pressure correlate with subjective assessments.

15. SUBJECT TERMS

FABRICS
SENSORS
PRESSURE
TEXTILES
COMFORT
CLOTHING
GARMENTS
PROTOTYPES
COMPARISON
EVALUATION
PERCEPTIONS
HUMAN BODY
MEASUREMENT
PRESSURE VALUES
PRESSURE SENSORS
FLEXIBLE PRESSURE
PRESSURE COMFORT
GARMENT PRESSURE
CLOTHING COMFORT
MILITARY CLOTHING
GT(GARMENT TEAMS)
TEST AND EVALUATION
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1. Preface

This work focused on investigating mechanical comfort of clothing and its evaluation. This work explored the use of very sophisticated flexible pressure sensors to objectively evaluate the pressure applied by a garment on the wearer's body. Both commercially available civilian garments and prototypes for military garments developed by the Garment Team at the Philadelphia University Laboratory for Engineered Human Protection (LEHP) were used in this study.

One of the objectives of this work was to establish a correlation between subjective evaluation of comfort and pressure values at various location in a garment.

The other objective was to extend this comparison of subjective and objective pressure values to prototypes of military garments developed by researchers at the Laboratory for Engineered Human Protection (LEHP).

In this study flexible single-point and multi-point array pressure sensors were used to measure pressure on the human body when specific actions were performed. Pressure measurements were compared to wearers' perceptions of pressure exerted by the garments.

This research was funded by the Department of Defense University Research Initiative. The grant award number was W911QY-04-1-0001. The funding agency was NSRDEC; the program supported was Warrior Systems Technologies.

2. Introduction

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2.1 Factors Affecting Comfort

Comfort is a perception resulting from complex interactions between wearer and fabric in specific climatic, physiological, and psychological conditions. Over years of research, it has been found that clothing comfort consists of three major sensory factors:

1. Thermal-Moisture Comfort

2. Tactile Comfort

3. Pressure Comfort

Figure 1 shows the three types of comfort along with their various attributes. The three sensory factors shown in Figure 1 contribute to most of the comfort of perception. The relative importance of individual factors varies with wearing conditions. For protective clothing, thermal-moisture comfort becomes the most important factor.

Tactile comfort and pressure comfort play important role when large body movements are involved. Thermal-moisture comfort is determined by the heat and moisture transfer behavior of clothing during dynamic interactions with human body and external environment. Tactile and pressure comfort is related to the mechanical behavior of clothing. Therefore, heat and moisture transfer and the mechanical behavior of clothing materials are the two major dimensions in determining the comfort and functional performance of clothing.

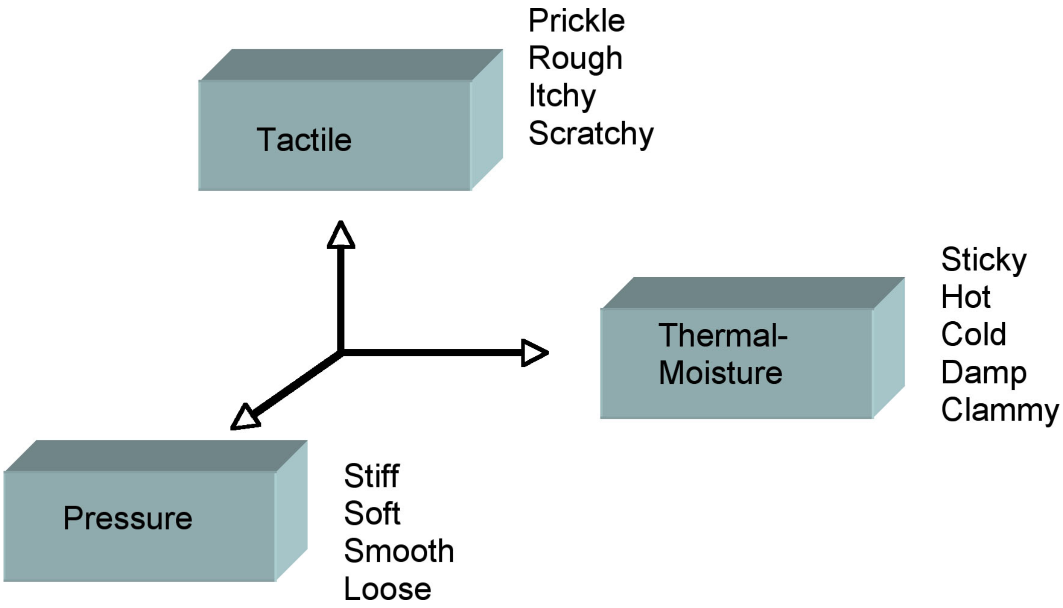


Figure 1. Sensory Comfort of Clothing

2.2 Literature Review

This work is focused on investigating mechanical comfort of clothing and its evaluation. A review of relevant literature is given below.

According to Fourt and Hollies, mechanical comfort of clothing is one of the three important conditions that define the ideal clothing [1]. The other two conditions are good hand and appearance. Evaluation of mechanical comfort of clothing through scientific means has been a very interesting topic of research since the 1930s [2]. The approaches to measure mechanical comfort of clothing can be experimental or computer simulated.

Experimental methods can again be divided into two categories: qualitative and quantitative.

Early research of clothing comfort was mainly qualitative, based on psychophysical surveys and questionnaires. With the development of new technology in sensors, it has become possible to conduct experiments to directly measure garment pressure on the body and, hence, objectively evaluate mechanical comfort of clothing on the body. At the same time, many researchers have developed procedures to predict clothing comfort by purely numerical methods.

The published research on garment pressure has focused on conducting wear trials to measure pressure and the relevant subjective sensations. Denton [3] observed that the discomfort level of clothing pressure is between 60 and 100 g/cm^2, depending on the individual and the part of the body on which the pressure is exerted. The range of pressure values is similar to blood pressure in the capillary blood vessels near the skin surface.

Based on the sensory evaluation and dynamic clothing pressure measurement, Sasaki et al. investigated the effects of dynamic clothing pressure [4]. They showed that the measured clothing pressure corresponded to the tightness sensation reported by the subjects.

Makabe et al. [5, 6, 7] measured garment pressure on the covered area at corsets and waistbands, and conducted a sensory test. They indicated that pressure at the waist is influenced by the area covered, respiration, and the ability of the garment to follow body movement. The subjective evaluation of clothing pressure at the waist showed that:

- no sense of discomfort is perceived when the pressure is in the range of 0 to 15 gf/cm^2,
- negligible or only slight discomfort is perceived when the pressure is in the range of 15 to 25 gf/cm^2, and
- extreme discomfort is perceived when the pressure exceeds 25 gf/cm^2.

Pratt and West [8] stated that there are three factors which influence the pressure of the garment on the body:

- shape of the body,
- mechanical properties of the garment, and
- style of the garment.

Chan and Fan [9] conducted direct measurements of girdle pressure on various positions of human subjects and studied the effects of the pressure on girdle functional performance in terms of body shaping, wearing comfort, and human physiology. They considered the effects of clothing pressure on the tightness rating as a subjective measure. Chan and Fan found that there was moderate linear relationship between the tightness rating and the logarithm of clothing pressure.

The relationship between the pressure sensation and clothing pressure was also studied by Okada [10]. He found that the pressure sensation at the waistline was linearly related to the logarithm of the pressure applied by a waist cuff band, which follows the Weber-Fechner Law.

Inamura et al. [11] reported that the wearing comfort of girdles was related to the tensile and shear properties the girdle fabrics. You et al. [12] worked on the garment pressure sensation relationships between subjective pressure sensation and objective pressure measured, for knit garments of different sizes and fabrics with different extensibilities. These researchers used pressure sensors in which the pressure range can be expected to be 0 to 0 kPa. The size of sensor cell was 10 x 10 mm and no more than 5 mm thick.

You et al. developed equations for describing the psychophysical mechanism of clothing-pressure perception under certain conditions.

They found that clothing comfort had a negative correlation with feelings of fettering, scratchiness, heaviness, and pressure, and had a poor correlation with feelings of softness and smoothness [13]. The garment fitness and fabric extensibility had great predictive power for the subjective pressure assessment.

Some researchers tried to totally eliminate subjectivity by using pressure sensors on a manikin. This method eliminated two variables: body size and body softness.

For the pressure measurement Yamada et al. [14] developed a special manikin to simulate the lower half of the human body. They used the dummy for the pressure measurement of panty hose and found very good agreement between the pressure on the human body, theoretically calculated pressure, and the pressure measured on the dummy when the dummy is covered with a compressible surface.

Fan and Chan [15] worked on establishing a method to predict the clothing pressure on the human body from the measured pressure on a conventional manikin by considering the differences between the human body and the manikin.

Chen et al. [16] used dummies designed for resuscitation practice to obtain clothing pressure with both normal standing posture and movement patterns. These researchers compared the data obtained from dummies with subjective test data to give the relationship of clothing pressure between the dummy and subject.

2.3 Pressure Sensors for Measurement of Mechanical Clothing Pressure

For measuring clothing pressure on the human body, sensors can be employed if they do not interfere with the functioning of the garment. A review of the developments in sensors for clothing applications is given below.

Komimami [17] developed air-packed sensors for clothing pressure measurement. The novelty of these sensors was that they were soft and compressible. Each sensor had an air bag that could be put between two contacted materials, and air pressure generated inside that air bag was measured. Ito [18, 19] further conducted research for measurements of clothing pressure on the human body using the sensors developed by Komimami.

Dunne et al. [20] presented initial research into the tracking of arm movements using a foam-based pressure sensor to record dynamic forces present in a worn garment structure in motion. A soft, washable polypyrrole-coated foam sensor was used in four locations around the arms, and resistance changes were recorded for all four sensors as the subject performed four arm movements. The results indicated that the responses of this sensor in these locations can adequately indicate upward, downward, and forward arm positions.

Ashruf [21] has given an overview of the currently available techniques that make use of single-sensor elements, as well as integrated arrays of sensors, to obtain pressure maps.

Sergio et al. [22] presented an approach for using capacitive sensing to decode the pressure information gathered as pressure was exerted over a broad piece of fabric. The proposed sensor included a distributed passive array of capacitors (capacitance depended on the pressure exerted on the textile surface) and an electronic system to acquire and process the subsequent capacitance variations.

A detailed overview of developments in apparel sizing, anthropometric data, development of sizing systems, hosiery sizing, testing for fit, and future expectations was given in an article by Pechoux and Ghosh

[23]. It discusses various methods for testing the fit of garments on live models, flat forms, stretch tests, and three-dimensional body scanner and computer simulation. The article discusses the advantages and disadvantages of various fit measuring methods.

From the literature it is clear that subjective evaluations are currently the most popular methods for garment pressure measurement. However, recent developments in flexible pressure sensors make it possible to measure garment pressure objectively.

The remainder of this report contains:

- a description of the methods and procedures used in this research
- a presentation of the results and a discussion of those results
- a presentation of conclusions drawn from the results
- recommendations for further study
- a list of works cited
- appendices containing physical properties data for the commercial garments tested, the questionnaire used to help establish a correlation between subjective and objective assessment of pressure on the body exerted by garments, and the consent form signed by research subjects in this study

3. Methods and Procedures

3.1 Overview

This work represents both subjective and objective studies of pressure-related garment comfort and was carried out in the following order:

1) Simultaneous subjective and objective study of mechanical comfort of a civilian, commercially available garment

- Subjective study through a questionnaire administered to volunteer subjects
- Objective garment-pressure measurement by flexible sensors

2) Objective study of the mechanical comfort of garment prototypes developed by the Laboratory for Engineered Human Protection (LEHP) at Philadelphia University; flexible sensors were placed on the subject's body to measure garment pressure.

For subjective evaluation of garment comfort, Likert scaling was used in this study [24]. Subjects were asked to express agreement and disagreement on a five-point scale. Each point is given a value from one to five. Thus, a total numerical value was calculated from all the responses.

3.2 Evaluating Civilian Garments

3.2.1 Subjects

Eleven male students at Philadelphia University were selected as subjects for the comfort wear trial. The subjects were volunteers who responded to an e-mail invitation to participate in the study. The mean and the standard deviation of the heights of the subjects are given in Table 1.

Table 1. Average Subject Height Data

No. of Subjects	Mean Height	Standard Deviation
11	175.26 cm (5 ft 9 in)	3.05 cm (1.2 in)

Subjects were chosen to approximately represent medium-sized male U.S. soldiers. This concern for height was required because the study will be used in evaluating comfort of military combat garments.

3.2.2 Garment

In this study, Dockers® brand regular fit cotton trousers, made by Levi Strauss & Co., were chosen. Trousers were bought to fit each test subject's waist and inseam. Physical properties of three cloth samples from the trousers were measured by the Kawabata Evaluation System; this information is in Appendix A.

3.2.3 Pressure Sensors

To measure pressure at various locations, the trousers were equipped with pressure sensors. Ultra-thin and flexible sensors from FlexiForce® were used so that interaction between fabric and skin was not affected. FlexiForce pressure sensors [21] are resistance-based sensors. Figure 2 shows a FlexiForce sensor.

Figure 2. FlexiForce Single-Element Pressure Sensor (tekscan.com)

The FlexiForce single-element force sensor acts as a force-sensing resistor in an electrical circuit. When the force sensor is unloaded, its resistance is very high. When a force is applied to the sensor, the resistance decreases. In Figure 3 the black straight line represents the theoretical calculated value of conductance vs. force. The graph also shows the force vs. resistance (curved blue line) and the measured conductance vs. force (purple line deviating only slightly from the straight line representing the theoretical conductance vs. force (1/R)). The conductance curve is linear and is therefore useful in calibration.

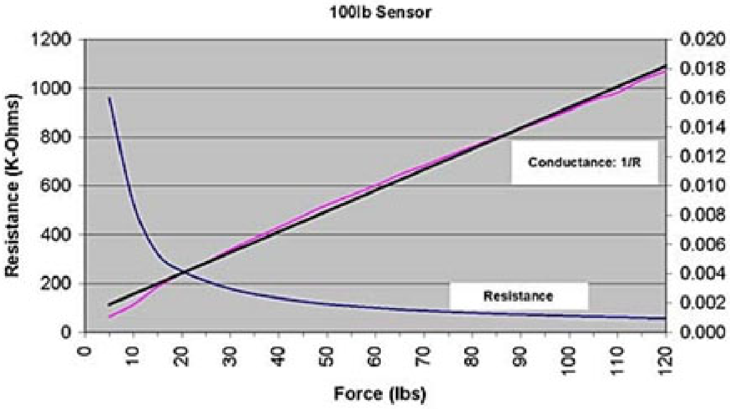


Figure 3. FlexiForce Resistance vs. Pressure, Force vs. Resistance, and Force vs. Conductance[21]

The resistance can be read by connecting a multimeter to the output leads. The sensor can also be used with an analog-to-digital converter circuit to transform the voltage across the sensor to digital output. Figure 4 shows a typical load vs. voltage graph obtained using an appropriate electronic circuit.

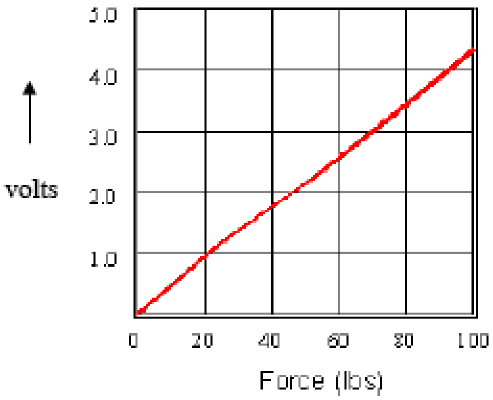


Figure 4. FlexiForce Sensor Load vs. Voltage[21]

The FlexiForce thin sensors were fitted on the inside of the trousers using adhesive tape. Sensors were connected to a potential-divider electronic circuit as shown in Figure 5.

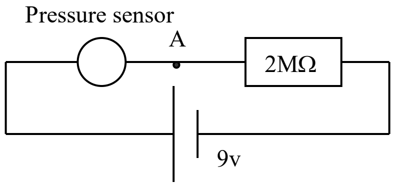


Figure 5. Potential Divider Electronic Circuit for Pressure Measurement

The output of point A was fed to an analog-to-digital converter that was connected to a computer for data collection.

3.2.4 Subjective Evaluation of Garment Comfort

3.2.4.1 Preparation

The procedure for subjective evaluation of trouser-wearing comfort was approved by Philadelphia University's Institutional Review Board. The following preparations were made for each test subject:

a) Subjects were contacted via e-mail.

b) Subjects who agreed to volunteer to participate in the study were required to sign a consent form (Appendix C).

c) Each individual was asked for his usual trouser measurement (waist and in-seam length). If the subject did not know his usual size, he was measured.

After a new pair of trousers for each test subject was purchased, the experiment was scheduled.

3.2.4.2 Experimental Procedure for Subjective Evaluation

The following procedure was followed for each test subject individually.

1) Subjects were sent to a dressing room and asked to change into the trousers equipped with FlexiForce sensors.

2) In a quiet room, the testing procedure was explained and each student was given a questionnaire (see Table 2).

3) Subjects were asked to perform two activities, three times each:

a) Knee bending: Raise a leg with 90 degree angle between thigh and shank, and with the thigh parallel to the ground.

b) Sitting: Assume a comfortable sitting position.

4) After performing each activity, subjects were asked to fill out the questionnaire.

Survey questions consist of psychophysical scaling used in rating subjective perception. The subjects were asked to rate the sense of pressure on a scale of 1 to 5.

3.2.4.3 Questionnaire

Table 2 shows the sample questionnaire that was given to each subject (see also Appendix B). Each subject was asked to indicate a number from 1 to 5 in each box.

1. Lowest
2. Low
3. Moderate
4. High
5. Highest

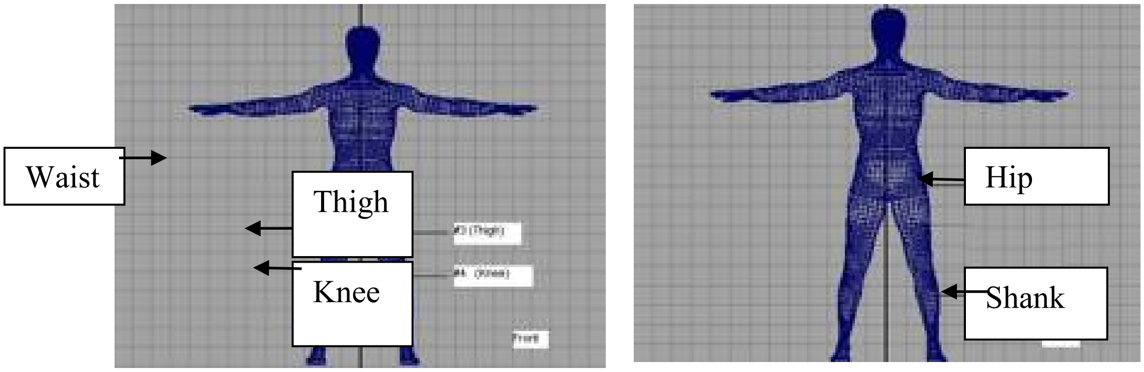
These numbers were used as rankings. For example, while grading the pressure sensation, a subject would give number 5 for the location where he had the tightest feeling and 1 for the location of the lowest tightness feeling.

Table 2. Questionnaire for Subjective Assessment of Comfort

Serial No.	Pressure Points	Pressure Sensation	Hindrance	Heaviness	Scratchy
1	Knee				
2	Thigh				
3	Waist				
4	Hip				
5	Shank				

3.2.5 Objective Measurement of Garment Pressure

Objective measurement was done during the same experimental session as the subjective evaluation of garment comfort. Figure 6 shows the locations where the thin film pressure sensors were mounted.



Front

Back

Figure 6. Pressure Sensor Locations

When each subject was asked to perform activities mentioned in the above section, pressures generated on the sensors by the press of the garment on the subject's body during the movements were captured by a computer as digital signals. The whole circuit of pressure sensors worked on a 9V compact battery; subjects were not in danger of receiving an electric shock.

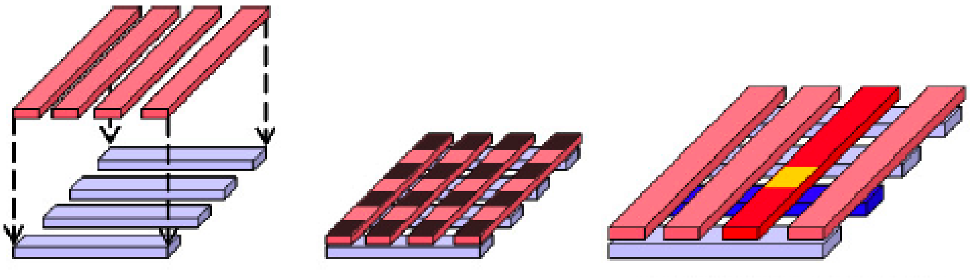
3.3 Evaluating LEHP Prototype Suits

3.3.1 Multi-Point Sensor Array

After analyzing the results obtained from the single-point sensor, it was decided to switch to a multi-point pressure sensor for evaluating the pressure applied by the LEHP prototype suits on human body. In dynamic measurements, single point sensor location could not be maintained exactly at the peak pressure region on the body. Since the sensors were mounted under static conditions and the measurements were taken under dynamic conditions, sensor locations could not be predetermined exactly.

A search of commercially available multi-point flexible pressure sensor technology revealed a recent development by Pressure Profile Systems. The company makes several types of flexible sensors of which the TactArray sensor was found to be most suitable for application to sense clothing pressure.

The TactArray sensor used in this research is an array sensor made of a flexible material. This sensor works on the capacitance principle to measure pressure developed at particular points over a small area. The capacitance sensor is built with a set of electrodes and a compressible dielectric matrix. The sensor used in this work consisted of a 16 x 16 array of electrode strips forming 256 capacitance points. Figures 7 a, b, and c show the arrangement of electrode strips, the capacitors formed at crossing points, and the addressing of individual capacitance points.



(a) (b) (c)

Figure 7. Structure of Pressure Profile Systems Array Sensors [25]

The conformable TactArray sensor, and its electrodes are built of a conducting electronic textile material. This design enables the sensor to be flexed in multiple radii conforming to the shape of arbitrary objects [27,28].

Table 3. Specifications for TactArray Sensors [26]

Characteristic	**Specification**
Max Pressure	200 kPa
Dynamic Range	300:1
Active Area	60 mm x 60 mm
No of sensing elements	256
Thickness	1mm
Temperature range	–20° C to 100° C
Sensor material	Conductive fabric
Conformable/moldable?	Yes
Stretchable?	Minimal

3.3.2 Conditioning Electronics

The sensors of Pressure Profile Systems are driven by proprietary electronics and can scan the electrodes at high speed. The system is sensitive to changes in capacitance less than 4 thousandths of a picofarad [29]. The 256-element sensor used in this work used a maximum sampling rate of 5kHz [30].

3.3.3 TactArray Visualization Software

The visualization software packaged with the sensors allows real time monitoring of pressure data. The data can also be exported for analysis using any spreadsheet application. The software displays and records maximum pressure, average pressure, total force, and contact area [31].

3.3.4 Determination of Sensor Locations

The locations where the sensor would be mounted were determined based on literature and on the results of the human factors testing conducted by the garment design team of the Laboratory for Engineered Human Protection. A human factors test was conducted with a subject who fits the measurements of the suit. Because the garment under investigation was a military suit, the requirements for comfort and the wearer's motions were different from those for commercial garments. During the test, the subject donned the suit and made motions specified by the U.S. military [36].

The subject performed mission-related movements like crawling and squatting, and routine movements, such as reaching as if climbing a ladder, and raising his arms above his head. At the end of the test, the subject was asked to identify areas of his body where he felt pressure from the suit.

The information gathered from the subject gave an idea of points on the garment where high stress was induced and helped to determine locations to place the sensor array.

The subject reported maximum pressure at the knee during the knee bending motion, at the hip during the squatting motion, and the elbow during the raising arms and reaching motions.

3.3.5 Mounting the Sensor

The TactArray sensor, which was 60 mm x 60 mm, was made of a conformable material. To prevent the sensor from damage during the test, it was placed in a pouch made of a thin, lightweight fabric. This pouch containing the sensor was securely mounted on the subject's body using very thin fabric fasteners; see Figure 8. First the sensor was mounted at the knee of the subject, where maximum pressure is generated during body movements. The subject was then asked to wear the first prototype garment, and all the donning protocols were followed. (For these protocols, see the LEHP companion technical report *Garment System Engineering for Chemically Protective Clothing* [37].)

Figure 8. Sensor Placement at the Knee

3.3.6 Pressure Measurement and Data Acquisition

After the sensor had been placed on his knee, the subject was then asked to raise the leg with the sensor as high as possible in the forward direction. Simultaneously, the data acquisition unit was used to capture the pressure signals from the sensor. The signals were transmitted to a computer through a USB interface. The transmitted data was available for live viewing in the visualization software and was concurrently recorded.

The subject was asked to do the procedure three times. The recorded data was then exported into a text file format that could be directly incorporated in a spreadsheet for statistical analysis.

Figure 9. Pressure Measurement Setup

The sensor was then re-positioned at the subject’s hip, and he was asked to perform the squatting motion while wearing the first prototype garment. The pressure generated at the hip was also collected.

The sensor was then mounted at the elbow of the subject, and while he was wearing the first prototype garment, the subject was asked to perform two routine army motions: raise both arms above his head and climb-and-reach-motion [36].

After collection of pressure signals for all sensor locations and test motions while the subject was wearing the first tested prototype, he changed into the second prototype to be tested. Collection of pressure signals was repeated for the same sensor locations and motions.

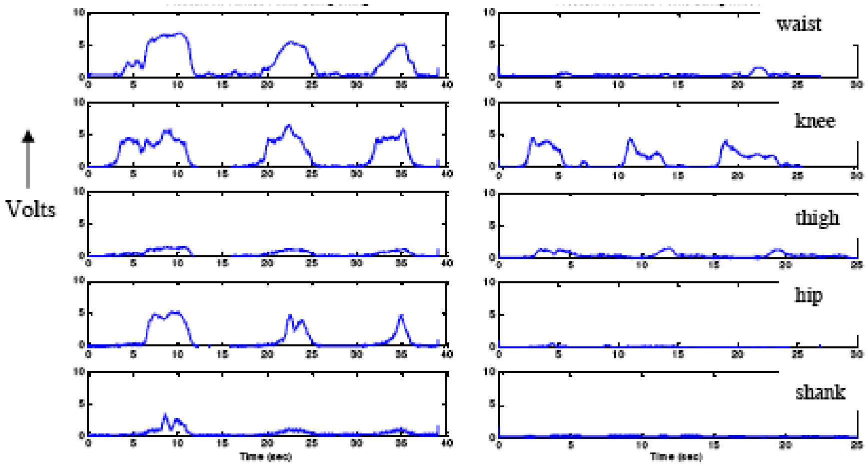
4. Results and Discussion

The two objectives of this work were to establish a correlation between subjective and objective measurements of garment mechanical comfort, and to extend the procedure to military garments.

Both objectives were achieved.

4.1 Assessment of Pressure Exerted by Commercially Available Trousers

Responses of single-point pressure sensors, located at various points in commercially-available Dockers trousers during sitting and knee bending are shown in Figure 10. The graphs show several cycles of movement of a subject.



Sitting *Knee Bending*

Figure 10. Graphs Obtained from Single-Point Pressure Sensors in Dockers Trousers

To make voltage readings comparable to the subjective feedback of pressure sensations at various locations, voltage readings were discretized in five levels. Tables 4 and 5 give scaled pressure measurements from sensors and corresponding subjective feedback on pressure sensation for eleven subjects. The scale went from 1 to 5 with 5 being the highest. The values in parentheses in the tables are subjective feedback.

Table 4. Sitting Position Objective (Single-Point Sensor) and Subjective Pressure Assessments for Subjects Wearing Dockers Trousers.

Values in Parentheses are Subjective Assessments

Subject No.	Waist	Knee	Thigh	Hip	Shank
1	2	5	2	1	1
	(2)	(5)	(3)	(1)	(2)
2	5	4	4	4	1
	(4)	(5)	(4)	(3)	(1)
3	5	1	2	1	1
	(3)	(5)	(3)	(4)	(2)
4	5	5	5	4	1
	(1)	(2)	(3)	(2)	(1)
5	4	1	5	5	1
	(3)	(5)	(4)	(3)	(1)
6	5	4	3	4	1
	(3)	(5)	(4)	(3)	(1)
7	4	5	3	5	1
	(3)	(5)	(3)	(2)	(1)
8	5	4	1	5	2
	(2)	(4)	(1)	(1)	(1)
9	5	4	3	3	1
	(3)	(3)	(3)	(2)	(1)
10	5	4	2	2	2
	(4)	(5)	(2)	(2)	(1)
11	1	4	2	2	1
	(1)	(5)	(4)	(3)	(2)

Table 5. Knee Bending Objective (Single-Point Sensor) and Subjective Pressure Assessment for Subjects Wearing Dockers Trousers.

Values in Parentheses are Subjective Assessments

Subject No.	Waist	Knee	Thigh	Hip	Shank
1	5	5	1	3	2
	(2)	(4)	(3)	(2)	(3)
2	5	2	3	3	1
	(4)	(5)	(4)	(3)	(2)
3	5	5	1	1	2
	(3)	(5)	(3)	(5)	(2)
4	5	1	3	1	1
	(1)	(3)	(2)	(1)	(1)
5	3	1	3	5	1
	(4)	(4)	(5)	(4)	(3)
6	5	3	1	1	2
	(5)	(4)	(3)	(4)	(1)
7	5	5	2	3	1
	(4)	(5)	(4)	(3)	(2)
8	3	5	4	1	3
	(1)	(4)	(3)	(1)	(2)
9	5	3	2	5	2
	(4)	(3)	(3)	(4)	(1)
10	3	4	1	4	1
	(4)	(3)	(1)	(5)	(1)
11	4	3	2	1	4
	(5)	(4)	(1)	(2)	(3)

Figures 11 and 12 show side-by-side comparisons of scaled pressure measurements and subjective feedback for the two activities of sitting and knee bending.

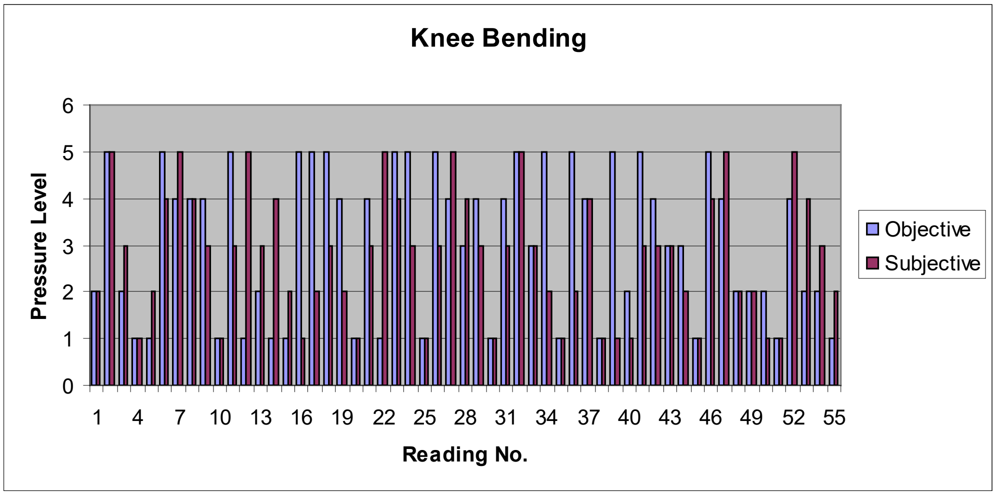


Figure 11. Comparison between Scaled Pressure Measurement and Subjective Feedback for Knee Bending in Dockers Trousers

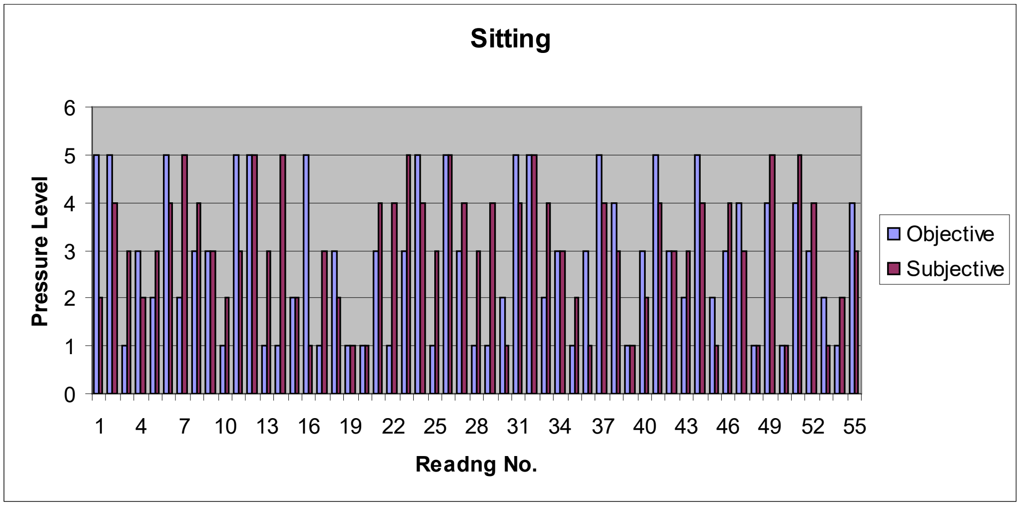


Figure 12. Comparison between Scaled Pressure Measurement and Subjective Feedback for Sitting in Dockers Trousers

There is a correlation of 0.40 between pressure measured by sensors and subjective feedback during knee bending and a correlation of 0.42 for sitting.

Another comparison was made by taking only the extreme (1 and 5) values of pressure sensation reported by subjects and corresponding values obtained from single-point pressure sensors. Higher correlations of 0.6 and 0.86 were obtained for knee bending and sitting in the second comparison.

The low correlation could be because in some instances the subjective feedback values were very different from pressure senor readings. These differences were probably because it was hard for the subjects to simultaneously perform an activity and remember pressure levels at five locations, and then to rank those levels accurately.

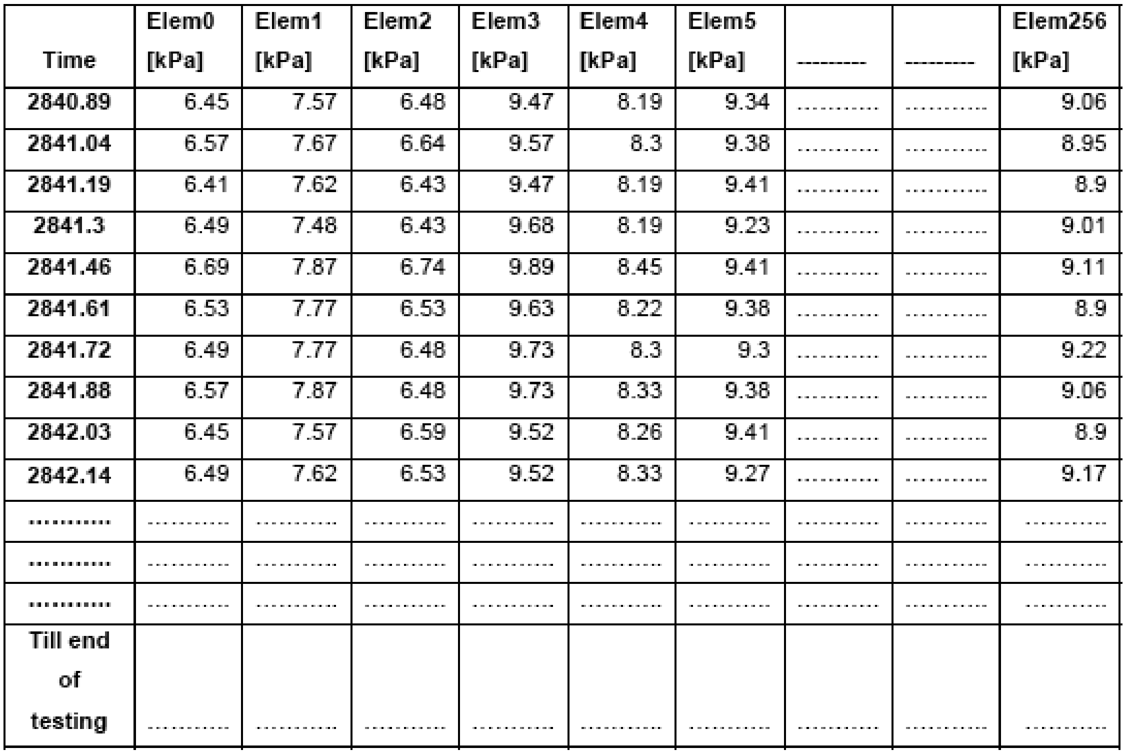
Therefore, in cases where subjects must perform many tasks simultaneously, objective evaluation should be used to determine garment comfort level and to know the points of discomfort in a garment while in use.

Another reason for low correlation could be slippage of single-point pressure sensors from their original positions, leading to inaccurate pressure readings. The single-point sensors have an extremely small measurement area, less than one square centimeter. During movement of the subject the sensor's location with respect to the subject's body changes, resulting in inaccurate measurements.

4.2 Assessment of Pressure Exerted by LEHP Prototype Garments

The objective garment pressure measurements carried out on the LEHP prototype garments with the multi-point array sensor provided data 7 to 8 times per second on all the 256 sensing points of the sensor, resulting in an extensive set of values. A sample is shown in Table 6.

Table 6. Objective Garment Pressure Measurements (Multi-Point Sensor) for Subject Wearing LEHP Prototype Garment



Time	Elem0 [kPa]	Elem1 [kPa]	Elem2 [kPa]	Elem3 [kPa]	Elem4 [kPa]	Elem5 [kPa]	---------	---------	Elem256 [kPa]
2840.89	6.45	7.57	6.48	9.47	8.19	9.34	………..	………..	9.06
2841.04	6.57	7.67	6.64	9.57	8.3	9.38	………..	………..	8.95
2841.19	6.41	7.62	6.43	9.47	8.19	9.41	………..	………..	8.9
2841.3	6.49	7.48	6.43	9.68	8.19	9.23	………..	………..	9.01
2841.46	6.69	7.87	6.74	9.89	8.45	9.41	………..	………..	9.11
2841.61	6.53	7.77	6.53	9.63	8.22	9.38	………..	………..	8.9
2841.72	6.49	7.77	6.48	9.73	8.3	9.3	………..	………..	9.22
2841.88	6.57	7.87	6.48	9.73	8.33	9.38	………..	………..	9.06
2842.03	6.45	7.57	6.59	9.52	8.26	9.41	………..	………..	8.9
2842.14	6.49	7.62	6.53	9.52	8.33	9.27	………..	………..	9.17
………..	………..	………..	………..	………..	………..	………..	………..	………..	………..
………..	………..	………..	………..	………..	………..	………..	………..	………..	………..
………..	………..	………..	………..	………..	………..	………..	………..	………..	………..
Till end of testing	………..	………..	………..	………..	………..	………..	………..	………..	………..

To evaluate the results, the pressure recorded at all the 256 locations was plotted on a graph against time. The graphs in Figures 15 and 16 show the pressure variations at different points on the sensor during the testing of LEHP prototype garments.

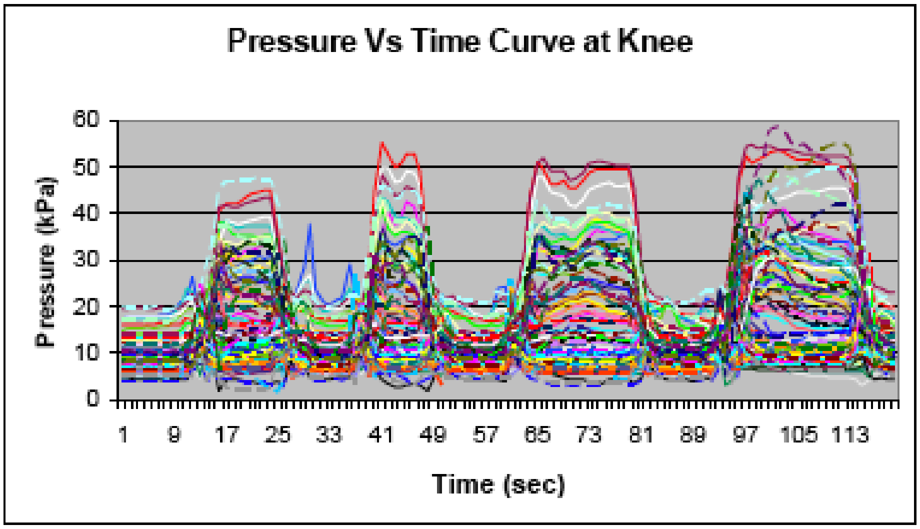


Figure 13. LEHP Prototype 1 Knee Pressure vs. Time (Multi-Point Sensor Array)

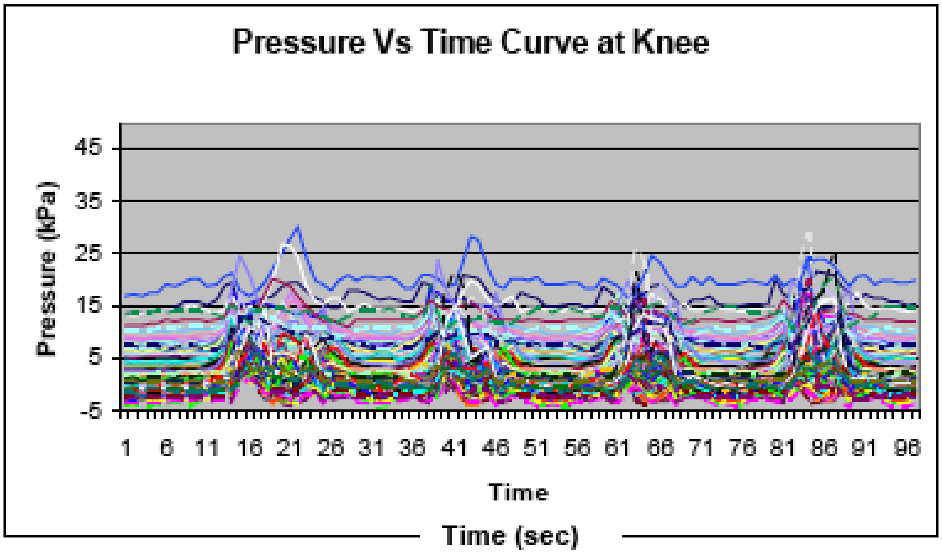


Figure 14. LEHP Prototype 2 Knee Pressure vs. Time (Multi-Point Sensor Array)

From the two graphs in Figures 13 and 14, it is evident that the pressure generated at the knee location is higher in the first prototype than the second prototype. The average of the peak pressures at all the 256 points for each time interval was calculated and found to be lower for the second prototype as shown in Table 7.

Table 7. LEHP Prototypes Average Peak Pressure at Knee

Location	LEHP prototype 1	LEHP prototype 2
Knee	32.91 kPa	20.90 kPa

The pressure at the hip during the squatting motion was plotted against time for both the prototypes. The graphs below in Figures 15 and 16 show the curve obtained, and it was found that the pressure for the second prototype was lower than for the first prototype.

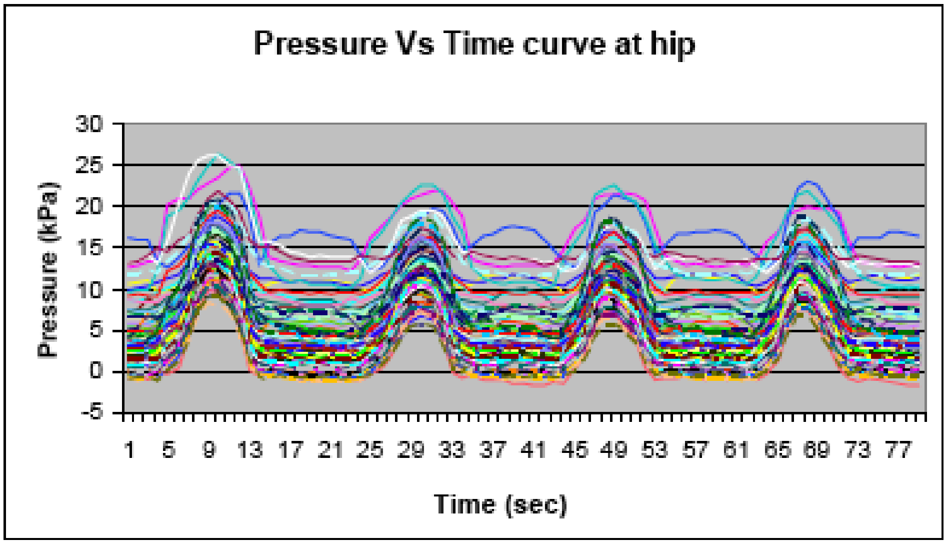


Figure 15. LEHP Prototype 1 Hip Pressure vs. Time (Multi-Point Sensor Array)

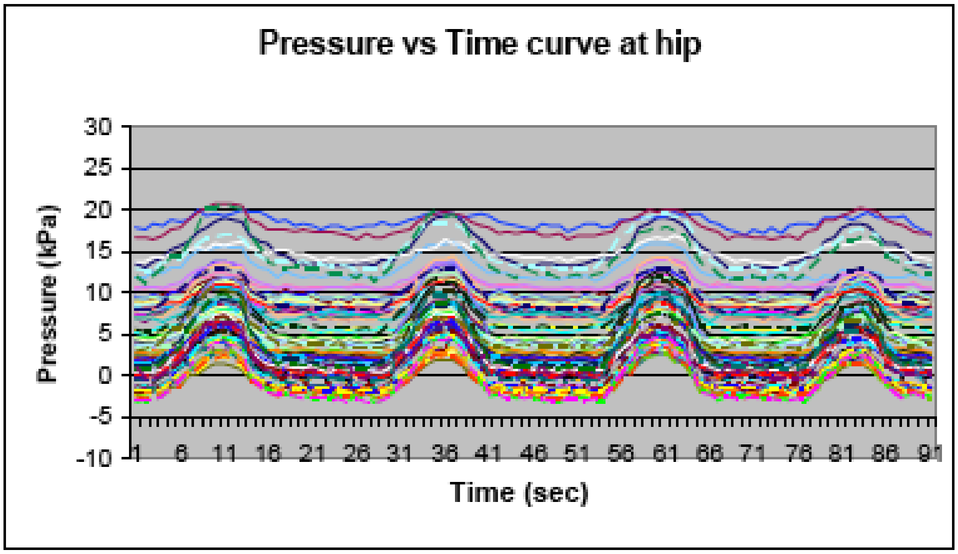


Figure 16. LEHP Prototype 2 Hip Pressure vs. Time (Multi-Point Sensor Array)

The average peak pressure recorded at the hip at all the 256 locations on the sensor for each time interval was calculated and found to be lower in the second prototype as shown in Table 8.

Table 8. LEHP Prototypes Average Peak Pressure at Hip

Location	LEHP prototype 1	LEHP prototype 2
Hip	22.35 kPa	18.49 kPa

Figures17 and 18 depict the pressure values during the reaching motion at the elbow. There is not a significant pattern because the pressure applied by the garment at the subject's elbow during the reaching motion did not impact the sensor at the correct location. Because of the relative movement of the garment and subject's body, the sensor could not be located at the exact peak pressure point. It can be seen that there are a few peaks in the first prototype, but there is no significant difference between the two. The peak pressure values of all the 256 sensor points for each time interval were averaged and found as below.

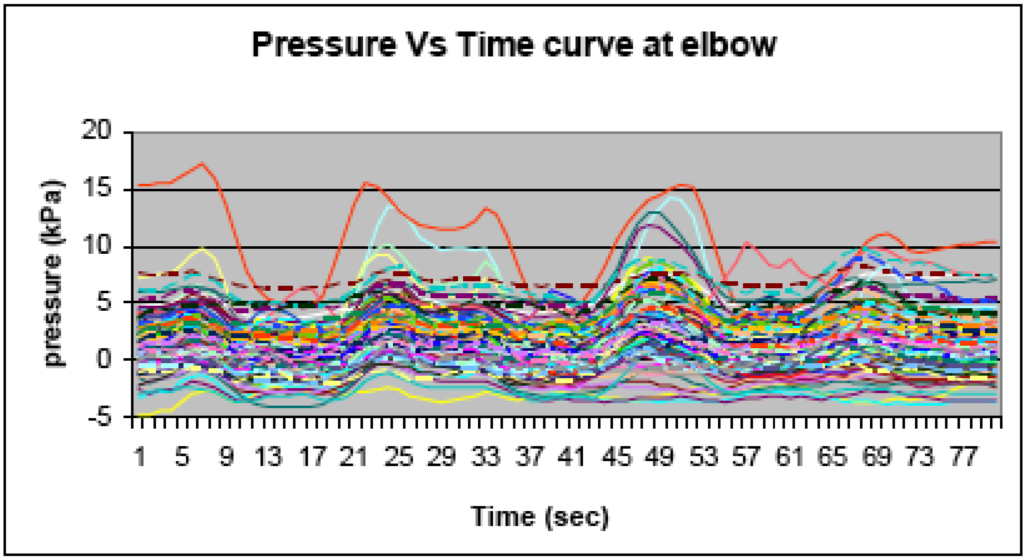


Figure 17. LEHP Prototype 1 Elbow Pressure vs. Time (Multi-Point Sensor Array)

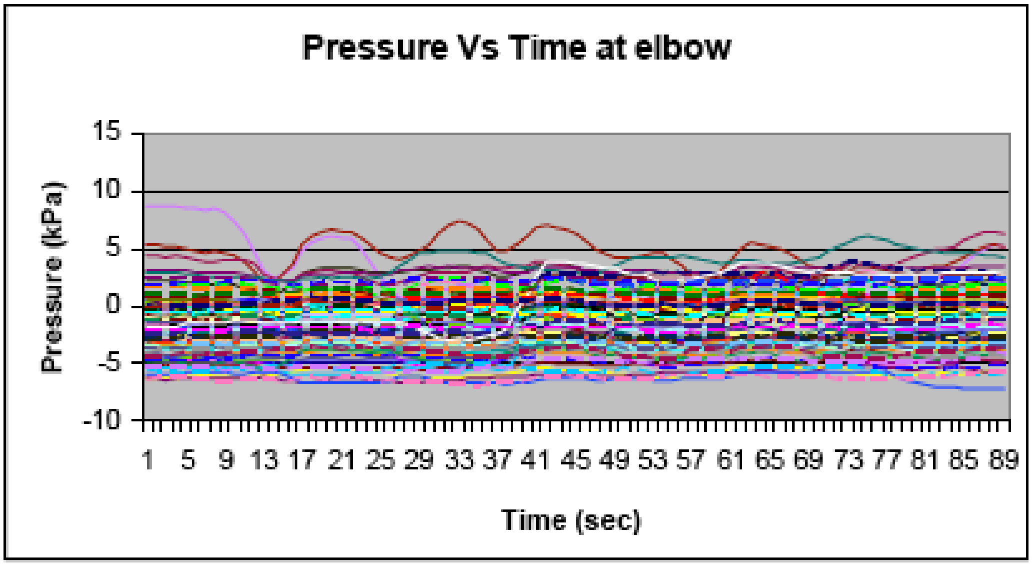


Figure 18. LEHP Prototype 2 Elbow Pressure vs. Time (Multi-Point Sensor Array)

Table 9 shows the relatively low peak pressure at the elbow for both prototypes.

Table 9. Average Peak Pressure at Elbow for LEHP Prototypes

Location	**LEHP prototype 1**	**LEHP prototype 2**
Elbow	15.60 kPa	14.26 kPa

The results of pressure analysis clearly show that the second prototype design, which the LEHP Garment Team intended to be more comfortable than the first prototype, achieved the Garment Team's goal. The human factors testing conducted by the LEHP also showed that the second prototype had better comfort than the first one [37].

The results of this pressure measurement study match with the subjective results from the human factors testing. Pressure measurement for evaluating the fit of garments is objective and not subject to the psychological factors that can affect perception of comfort.

5. Conclusions

A method has been developed and validated to objectively evaluate garment pressure on the human body. In the first part, subjects evaluated garment pressure feelings as the subjects went through motion sequences. Civilian, commercially available trousers were used as the test garment. Eleven subjects evaluated garment pressure at several locations. For objective evaluation of pressure, a flexible pressure sensor of resistive type from FlexiForce was used. The single-point sensor measures normal pressure applied by the garment on the body. Quantitative pressure measurements were compared with the results of subjective assessment, and good correlations were found. Correlations were better when only the extreme values of subjective feedbacks were compared with corresponding objective measurement.

For evaluating LEHP prototype garments for mechanical comfort, conformable array pressure sensors were used to collect pressure data at various locations of the garment. The two prototype garments developed for the military through the Laboratory for Engineered Human Protection were evaluated and compared. The results showed that the pressure comfort in the second prototype was better than the first. These differences were due to the design modifications in the second prototype. The methods used in this study enable researchers to determine points of high pressure in a garment; this determination helps in improving the design. The objective measurement methods used in this study also help in comparing pressure comfort of many garments without going through time-consuming subjective evaluation.

This study confirms other researchers' conclusions that objective measurements of garment pressure can be correlated with subjective assessments.

It is clear that objective measurements should be carried out with multi-point sensors on the subject's body to avoid inaccurate results from movement (relative to the subject's body) of single-point sensors. The conformable, multi-point array sensor used in this study is very effective in capturing garment pressure applied on the human body.

The results of this study indicate that the modification of flat patterns for the second LEHP prototype based on the objective pressure measurements resulted in a more comfortable garment.

6. Recommendations

It is recommended that similar studies be conducted comparing subjective and objective evaluations of garment comfort. In the subjective evaluation the CALM (Comfort Affect Labeled Magnitude) scale, developed by Cardello et al., could be used in place of the Likert scale [2]. It is expected that use of the CALM scale would remove some of the difficulty encountered by subjects using magnitude estimation and ranking procedures.

In the pressure evaluation using sensors, a more sophisticated method to mount the sensors can be employed, as the method used in this study is labor intensive. A wireless device could be incorporated into the sensor to transfer the signals to a computer, making the pressure measurement procedure less complicated. Also, future technological developments will make it possible to simultaneously record pressure sensations at various points on the garment.

As LEHP develops more prototype garments, they could be assessed for mechanical comfort, and a pressure-measurement-based procedure could be established for altering flat patterns.

This document reports research undertaken at the U.S. Army Combat Capabilities Development Command Soldier Center, Natick, MA, and has been assigned No. Natick/TR-22/012 in a series of reports approved for publication

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Appendix A – Physical Properties of Civilian Garment Used in Study

This appendix presents the physical properties of fabrics of the Levi Strauss & Co. Dockers brand cotton trousers used in the study, as measured using the Kawabata Evaluation System-Fabrics instruments [32,33,34].

The tests were carried out at the Materials Evaluation Laboratory at Philadelphia University.

Tensile Properties

Young's Modulus (E) is the modulus of elasticity which gives an estimate of the tensile stiffness of a given material. It is defined as the ratio of change in stress to change in strain. This can be experimentally determined from the slope of a stress-strain curve created during tensile tests conducted on a sample of the material on a KES-FB1 instrument.

Table A1. Tensile Properties of the Samples from Dockers Trousers

Samples	WT gf.cm/cm^2	LT *dimensionless*	RT %	EM mm
1 (warp)	-9	0.695	31	-5.19
1 (weft)	-10.3	0.7	44.1	-5.92
2 (warp)	-7.8	0.746	31.7	-4.22
2 (weft)	-9.3	0.748	43.5	-5
3 (warp)	-9.5	0.669	33.6	-5.7
3 (weft)	-9.7	0.775	43.1	-5.04

where:

WT – Tensile Energy while stretching the fabric to maximum force (gf.cm/cm^2)
LT – Linearity (dimensionless)
RT – Tensile resilience (%)
EM – Maximum Extension (mm)

Bending Properties

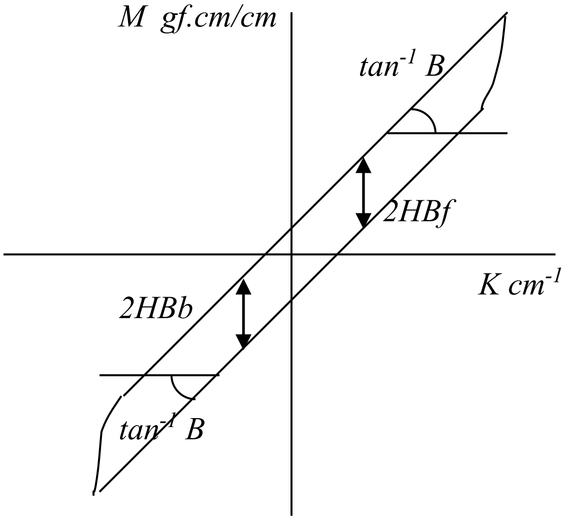

Figure A1. Typical Bending Test Diagram [33]

To find bending rigidity, B, the average of the two slopes obtained from KES-FB2 from Figure A1 is taken [33]. One value is when the sample is bent with its face surface outside (*Bf*) and the other is when the sample bent with its face surface inside (*Bb*). This leads to

$$B = \frac{\mathrm{Bf} + \mathrm{Bb}}{2}$$

where:

B= Bending rigidity per unit width ($\mathrm{gf.cm}^2$/ cm)

Similar to the method of bending rigidity, the method of finding bending hysteresis, 2HB, is to average the two hysteresis widths at curvature ±1 is taken. Thus,

$$Mean\ \ 2HB = \frac{2(\mathrm{HBf} + H\mathrm{Bb})}{2}$$

The bending properties of the samples are in Table A2.

Table A2. Bending Properties of the Samples from Dockers Trousers

Samples	Forward B	Forward 2HB	Backward B	Backward 2HB	Mean B	Mean 2HB
1 (warp)	0.206	0.231	0.148	0.213	0.174	0.222
1 (weft)	0.095	0.165	0.141	0.156	0.118	0.161
2 (warp)	0.202	0.233	0.705	0.299	0.14	0.266
2 (weft)	0.151	0.206	0.223	0.24	0.187	0.223
3 (warp)	0.259	0.161	0.32	0.156	0.146	0.158
3 (weft)	0.121	0.147	0.191	0.182	0.156	0.164

Shear Properties

The shear modulus is the elastic modulus that estimates the deformability of a material when a force is applied parallel to one face of the material while the opposite face is held fixed. Figure A2 shows the shear graph obtained from KES-FB1.

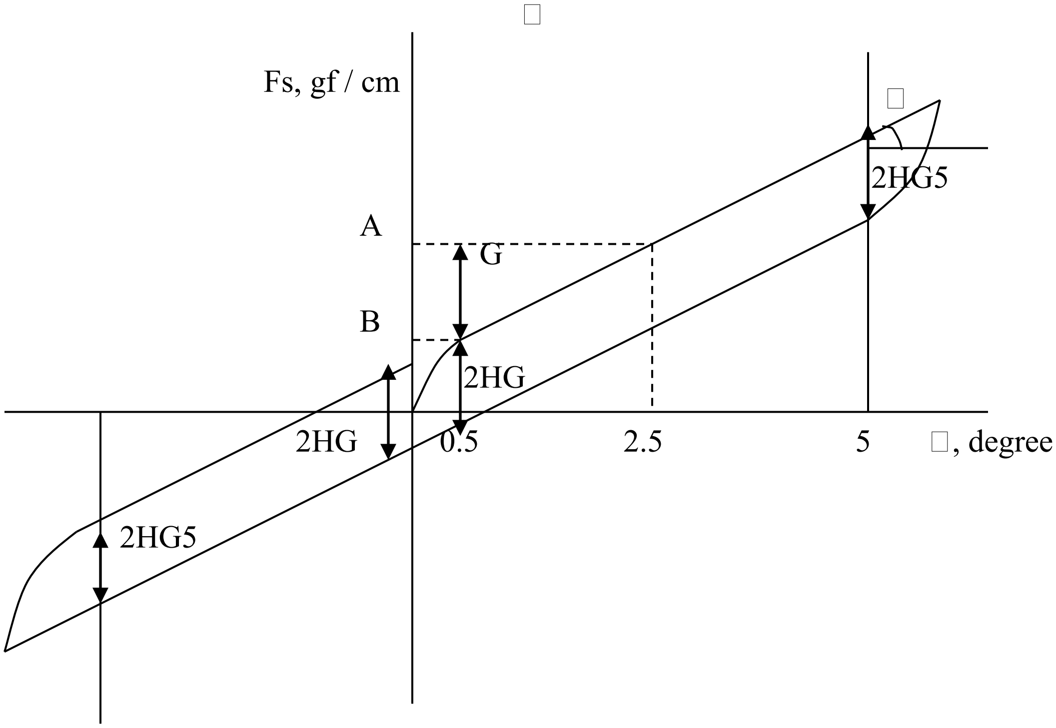

Figure A2. Typical Shear Test Force-Shear Angle Curve [32] where:

G: The slope measured between ø = 0.5 and 2.5º (gf/cm.degree)
2HG: Hysteresis of Fs at ø = 0.5º (gf/cm)
2HG5: Hysteresis of Fs at ø = 5º (gf/cm)
MEAN: Average of these values for positive and negative curves on warp and filling

Table A3 shows the shear properties of the samples.

Table A3. Shear Properties of the Samples from Dockers Trousers

Samples	Forward G gf/cm.degree	Forward 2HG gf/cm	Forward 2HG5 gf/cm	Backward G gf/cm.degree	Backward 2HG gf/cm	Backward 2HG5 gf/cm
1 (warp)	1.44	2.46	5.5	1.32	3.14	6.27
1 (weft)	1.17	1.88	4.64	1.2	2.57	3.12
2 (warp)	1.63	3.14	6.44	1.87	4.27	9.7
2 (weft)	1.24	2.78	5.79	1.68	4.04	8.1
3 (warp)	1.67	2.9	5.94	1.44	3.41	6.76
3 (weft)	1.52	2.58	6.44	1.14	2.91	4.94

Surface Properties

The surface properties of fabric, which consist of coefficients of friction and surface roughness, were measured. The results are shown in Table A4.

Table A4. Surface Properties of the Samples from Dockers Trousers

Samples	Forward Coefficient of Friction	Forward Standard Deviation of Coefficient of Friction	Forward Surface Roughness	Backward Coefficient of Friction	Backward Standard Deviation of Coefficient of Friction	Backward Surface Roughness
1 (warp)	0.218	0.014	2.05	0.197	0.0115	2.1
1 (weft)	2.58	2	5.65	2.36	1.91	5.38
2 (warp)	2.37	1.78	5.86	2.11	1.82	5.93
2 (weft)	2.12	1	1.99	2.08	1.18	1.63
3 (warp)	2.7	1.91	3.18	2.6	1.97	3.31
3 (weft)	2.3	1.29	2	2.1	1.06	1.86

Appendix B – Questionnaire Used to Assess Comfort of Civilian Garment

Questionnaire

Test Objective

This test is being conducted to establish a correlation between subjective and objective garment wearing pressure on the body.

In the table below, please indicate a number from 1-5 for each box.

1. Lowest
2. Low
3. Moderate
4. High
5. Highest

For example, while grading the pressure sensation, give number 5 for the location where you have the tightest feeling and 1 for the location of the lowest tightness feeling.

Serial No.	Pressure Points	Pressure Sensation	Hindrance	Heaviness	Scratchy
1	Knee				
2	Thigh				
3	Waist				
4	Hip				
5	Shank				

Appendix C – Informed Consent Form Used in Study

Informed Consent Form

INFORMED CONSENT FOR Objective Evaluation of Garment Comfort

Philadelphia University

Title of project: Objective Evaluation of Garment Comfort

Person in charge: Muthu Govindaraj

Office: 28A, Hayward Hall

email: govindarajm@philau.edu

1. This section provides an explanation of the study in which you will be participating:

A. The study in which you will be participating is part of a research intended to evaluate the comfort of garments. By conducting this study, the researcher hopes to improve mobility and comfort of garments including military garments. The researcher is a faculty member in Philadelphia University's School of Engineering and Textiles.

B. If you agree to take part in this research, you will be asked to wear a garment (a pair of pants) provided by the researcher. You will be asked to perform a standing up and sitting down routine for a maximum of six times. During the above procedure you will be asked to describe the comfort of the garment on a scale of 1 to 5. Sensors embedded in the garment will be collecting body/clothing pressure data during the body movement procedure.

C. Your participation in this research will take a total of 45 minutes.

2. This section describes your rights as a research participant:

A. You may ask any questions about the research procedures, and these questions will be answered. All questions should be directed to Prof. Muthu Govindaraj, the person in charge of the research.

B. Your participation in this research is confidential. Only the person in charge will have access to your identity and to information that can be associated with your identity. In the event of publication of this research, no personally identifying information will be disclosed. To make sure your participation is confidential, the data will not be associated with your name as soon as the data collection is over.