ABSTRACT

BURCHETT, MELISSA MAUD. Development of a Comfort Measurement Matrix.
(Under the direction of Dr. William Oxenham.)

Comfort has been shown to be a key determinant in textile product sales, yet as a concept, it is elusive. Comfort is comprised of a series of interactions with the human body and its environment. Comfort thus varies by end-use and the individual whims of the wearer or user. In order to study comfort, efforts were begun with fabric hand.

The Kawabata Evaluation System (KES-F) is known as the most complete method of evaluation for fabric hand and comfort characteristics, however, the breadth of information, time, and expense involved in this system has rendered it obsolete for use by the US textile industry, especially within the manufacturing environment. The current research is thus focused on the development of a more simplistic objective test method, and one that is suited to the needs of the industry.

Two methods were identified for use in this research as potential alternatives to KES-F. These are the CSIRO Fabric Assurance by Simple Testing (FAST) and a Ring Pull-Through (RPT) method. Trials were run on six fabric types, all six of which displayed variations in finishing treatments. Results from the two objective methods were compared to rankings from a subjective fabric hand evaluation, conducted in the College of Textiles at North Carolina State University.

The results show that the RPT method is able to discriminate between finished styles of a fabric type at a similar level to that of human judges. Additionally, multiple regression models for all test data suggest the strongest correlations between subjective preference data and FAST-3 extension variables. RPT peak load and area values also showed strong negative correlations with FAST-3 extension ratings, indicating the combined use of the RPT device and an extension test as a promising predictor of subjective comfort preferences. A matrix, or methodology, for utilizing these methods is proposed.

DEVELOPMENT OF A COMFORT MEASUREMENT MATRIX

by

MELISSA M. BURCHETT

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APPROVED BY:

Dr. William Oxenham
Chair of Advisory Committee

Dr. Traci A. May Lamar
Committee Member

Dr. Pamela Banks-Lee
Committee Member

Chris Moses
Technical Advisor

Dr. Henry Boyter, Jr.
Technical Advisor

BIOGRAPHY

Melissa Burchett was born in Durham, North Carolina. Upon graduation from high school, Melissa attended Cornell University in Ithaca, New York. There she graduated with a B.S. in Textiles, with a concentration in Apparel Design. Melissa also studied abroad in Australia in the fall of 2002, through the School for International Training. Upon graduation from North Carolina State University's College of Textiles with a Master of Science in Textiles, Melissa has plans to gain knowledge about the textile industry via a position in manufacturing.

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CHAPTER I

1 Introduction

Fabric comfort is based on a mix of performance and aesthetics. The issue with studying comfort is that, as a concept, it is elusive. It is comprised of a series of interactions with the human body and its environment. Comfort thus varies by end-use and the individual whims of the wearer or user. The importance of comfort cannot be overestimated, however, as comfort has been shown to be a key determinant in textile product sales. Current marketing research shows that consumers are choosing apparel comfort over style across all age groups (29).

For many textiles, especially outerwear fabrics, an equally high value is placed on the fabric hand and comfort attributes as on the color of the fabrics (27). However, the color of a fabric can be measured objectively, with the aid of a spectrophotometer. In terms of a fabric's hand and comfort, though, there is still no agreed-upon method for objective measurement of these properties within the textile industry. Evaluations by companies are still frequently subjective assessments.

A system that was designed for this purpose, the Kawabata Evaluation System, has not fulfilled the needs of the textile industry. The Kawabata's strength lies in the breadth of its data collection, however the system is costly, time-consuming and it requires a high level of expertise to operate. The unavailability of the Kawabata Evaluation System due to cost, time, and upkeep restraints has rendered it obsolete for use by the US textile industry, especially in the manufacturing setting. Therefore it is important to develop a simpler method to satisfy the needs of the industry.

1.1 Purpose

The purpose of this research is thus to provide industry with an additional metric whereby decisions can be made (pass or fail) based on values for fabric hand and comfort. The goal is that this method would provide a high speed and low cost alternative to the currently available methods, such as subjective assessments and the Kawabata Evaluation System (KES-F).

1.2 Objectives

In order to approach the issue of comfort, efforts have begun with an analysis of fabric hand, a property related to textile comfort. Fabric hand is composed of a simpler set of mechanical properties than those at work in fabric comfort. With that said, the following are the objectives of this research:

RO1: To identify a few potential methods that could serve as alternatives to KES-F in the objective measurement of fabric hand.

RO2: To conduct fabric hand evaluation trials on appropriate sample sets using these methods.

RO3: To develop these simple methods into more effective tools for the objective measurement of fabric hand.

RO4: To compare these methods with a subjective assessment.

RO5: To construct a matrix, or methodology, that incorporates these methods to use as the basis for a larger comfort measurement system.

In response to the first objective, two simple methods have been chosen for this research. The first, a pull-through apparatus, termed Ring Pull-Through (RPT), was chosen for its simplicity and adaptability. This is a method that has been studied by the Institute of Textile Technology (ITT) in the past (30). The RPT test method simply records the force required to pull fabric through a ring or orifice on a tensile testing machine. This instrument is easily adapted to a testing laboratory in a manufacturing facility, and our research is looking to refine this method so that more sophisticated information can be obtained. The adjustment of variables such as ring diameter, ring shape, crosshead speed, and mounting procedure will be performed in an effort to obtain information about the hand of sample fabrics.

The CSIRO Fabric Assurance by Simple Testing (FAST) system was chosen as a measurement system that could provide more information than the RPT testing, yet far less than the Kawabata. Additionally, FAST is commercially available, easily operable, and relatively quick (four simple procedures).

1.3 Significance of Research

Textile products are eventually discriminated by the consumer using a subjective assessment, and subjective assessment traditionally formed the basis of fabric evaluation for the textile and apparel industries. However, there are a number of reasons why the industry is moving towards the objective measurement of fabric hand and comfort. These include the increased automation in textile processes, the need for “quick response” in the industry, the ambiguity associated with subjective assessments, and finally, the issue of the loss and replacement of experienced judges (11).

Research into the objective measurement of fabric hand and comfort is therefore valuable to the industry. Fabric handle and other parameters contributing to comfort are essential to the quality, fitness-for-use, sales, and overall customer satisfaction of textile products. However, the functional requirements of textile products necessitates the use of various mechanical and chemical finishing treatments, all of which can affect the hand and overall comfort performance of a fabric.

Furthermore, an objective measurement system could be a powerful tool for companies that are doing product development work or optimizing a fabric to meet a customer's needs. Additionally such a system could aid in the process of making sourcing decisions.

1.4 Definitions

The two terms "fabric hand" and "comfort" will be used frequently in this research. To aid in an understanding of the difference in meaning between these terms, the following definitions are given:

HAND *n.*

- The perceived overall aesthetic quality of a fabric (16);
- The quality of a fabric assessed by the sense of touch, concerned with the subjective judgment of roughness, smoothness, harshness, pliability, thickness, etc (7);
- Implies evaluation of fabric reaction to different modes of low stress deformation imposed by the human hand (7);
- Those components, qualities, attributes, dimensions, properties or impressions which make the sensation of touching one fabric different from that of touching another (2).

COMFORT *n.*

- Phenomenon connected to individual physical and psychic sensitivity;
- Freedom from pain and from discomfort, a neutral state. In total, it is the psychological feeling of the wearer, given certain environmental conditions and activities (19);
- A performance parameter relating to the wearability of the garment, encompassing such properties as wicking, stretch, hand (1).

Given these definitions, it can be inferred that fabric hand is used to describe the mechanical and physical properties of fabric that give it its touch or feel characteristics. However, comfort expands on this and includes the interaction of the textile product with the physiological processes of the body in such a way as to elicit either a positive or a negative response.

Other definitions for textile terms related to this research are listed below:

COMPRESSIBILITY *n.*

- Ease of squeezing (20).

EXTENSIBILITY *n.*

- Ease of stretching (20).

EXTENSION *n.*

- The increase in length of a specimen during a tensile test, expressed as a percent of the gauge length or nominal gauge length (9).

FABRIC OBJECTIVE MEASUREMENT *n.*

- A term used to describe a collection of instruments and testing procedures for the evaluation of low-strain mechanical properties of small fabric samples (9).

FLEXIBILITY *n.*

- Ease of bending (20).

GAUGE LENGTH *n.*

- The original length of that portion of a specimen over which strain or change is determined (9).

HYGRAL EXPANSION *n.*

- Reversible change in fabric dimensions that occurs when the moisture content of the fabric is altered (4).

RELAXATION SHRINKAGE *n.*

- Irreversible change in dimensions that occurs when a fabric is relaxed in steam or water (4).

SANFORIZING *n.*

- A controlled compressive shrinkage process used principally for cellulosic fibers (9).

SURFACE CONTOUR *n.*

- Divergence of surface from plane (20).

CHAPTER 2

2 Review of Literature

Previous work relating to the evaluation of fabric hand and comfort has been reviewed. The focus of this literature review is to examine the ways in which researchers have evaluated fabric hand and comfort, throughout history and into the present. Of primary interest are current objective test methods, for that is the focus of this research.

2.1 Subjective Testing

Subjective assessment of fabric hand traditionally formed the basis of fabric evaluation for the textile and apparel industries (12). Subjective assessments of fabric hand by human judges rely on psychophysical approaches, a type of psychology dealing with the relationship between physical stimuli and sensory response (7). Though textile products are eventually discriminated by the consumer using their own individualized forms of subjective evaluation, this method as an industry evaluation tool has many issues.

One of the issues with subjective evaluations is that there is a large degree of variation associated with the procedures, with companies often performing very informal evaluations. For instance, accounts of managers sitting in a boardroom rubbing fabrics as the sole subjective evaluation method for a company leads to little control over test variables and poor accuracy.

The American Association of Textile Colorists and Chemists (AATCC) has a test method for subjective fabric hand evaluation, AATCC Evaluation Procedure 5, however this method leaves a lot of leeway for the test designer and proctor. Using this method, test samples are handled and ranked by comparative assessments against a specified reference fabric. Reference fabrics have to be supplied by the proctor, as there are no specified universal standards available for purchase (2).

The precision of this as a test method has not been established, however, and the test consists of attribute data which must be analyzed using chi-square or t statistics for determining significance. Great effort and preparation must be taken in this test method to ensure unbiased judgment, and the test calls for a very sterile environment and untouched samples (2).

There are many varieties of subjective evaluations used in companies and academia today. Subjective evaluations can be generally broken down into two types, direct and comparative. Direct, or absolute, methods are based on the sorting of individual textiles according to a subjectively defined ordinal grade scale (0-very poor, 6-excellent). Comparative methods consist of an evaluator sorting according to the subjective criteria of evaluation (ordering from most pleasant hand to worst hand) (32).

Additionally, these comparative methods, or relative ranking methods, consist of the "paired method" or the "all fabrics at a time" method. The paired method is the method used by the majority of studies in this review. Using this method, two fabrics are presented at a time and one is chosen as being superior for a particular attribute. All possible pairs are presented in random order and the total number of times that a fabric is judged better in the pairing becomes a fabric's "rank score". This type of test method can help eliminate the bias of fatigue that can affect judges (32). The all fabrics at a time method, used in this research, can be used when the sample set is so large that the paired method is deemed too unwieldy, and also when the variation between fabrics is so slight that it is helpful to include a range of fabrics in each evaluation set. These types of evaluations can lead to results that are more difficult to analyze, however (7).

One of the most important steps of a subjective evaluation is to define the semantics that are going to be used to evaluate fabrics in the testing (7). Two types of descriptors are normally used in subjective evaluations, singular and bipolar. With singular descriptors, evaluators are judging fabrics based on a term, such as stiffness, smoothness or softness. They are to rate fabrics based on how much of this one quality the fabric possesses. With bipolar descriptors, contrasting adjectives are used to place fabrics along a scale for a particular fabric quality, such as limp to crisp (32).

Despite the continued use of subjective evaluations, in some form or another, there are a number of reasons why the industry is moving towards objective measurements. These include the increased automation in textile processes, the need for “quick response” in this industry, and the communication problems that arise with subjective evaluation assessments of fabric attributes. The issues of the loss and the necessary replacement of experienced judges also contribute to the need for objective testing instrumentation (11).

2.2 Variable Definition for Objective Testing

In order to develop instrumentation for picking up differences in fabrics relating to fabric hand and comfort, the variables to be measured had to be defined. Peirce was the first researcher to try to extract numerical values from the elements comprising the physical sensations felt when touching fabrics. A series of papers published in the 1930s identified the properties of bending, lateral compression, thickness, extension, and surface characteristics (surface friction) as being significant to fabric handle (25).

In addition to the isolation of these properties, Peirce listed some general attributes of fabrics that could lead to numerical variations in these properties. Peirce stated that the density and stiffness of a fabric is influenced by the raw material used and the count and twist of the yarns, these being defined at early stages of production. Additionally for woven fabrics, the amount and type of warp size, the number of picks and ends, and warp tension are influential. Peirce goes on to state that the use of either sulfuric acid or starch (as a size or filling) has a stiffening effect due to the cementing or welding of fibers that occurs with these substances. Also, the swelling in mercerization brings hairs into intimate contact, thus increasing stiffness. In the latter stages of production, Peirce found that dyeing reduces stiffness, while heavy printing increases stiffness (25).

The work of a group of Swedish researchers led by Lindberg was the first to deal with properties specifically related to fabric tailorability and apparel appearance. Identified were the properties of fabric tensile and shearing, bending behavior, and fabric formability (11). Formability is a term derived by Lindbergh, relating to the relationship between fabric properties and performance in garment manufacture. Formability is a measure of the extent to which fabrics can be compressed in-plane before buckling and thus can be used to predict seam pucker. Formability is related to bending rigidity and extensibility. This term is now used as a parameter in FAST testing (7).

A group of researchers at Leeds University in the United Kingdom led by Grosberg, developed the first thorough examination of fabric mechanical properties. Key properties were identified as tensile, bending, buckling, shear, and compression (11).

2.3 Objective Testing

Based on the work of Peirce and others in isolating variables for objective testing, there have been a number of attempts at instrumentation to quantify handle by simple methods. Examples include the Thwing-Albert/Clupak Fabricometer and Handle-o-Meter, as well as the King Fabric Stiffness Tester. These methods were soon overshadowed, however, by the Kawabata Evaluation System (13). Credited as the first instrumentation designed to measure the low-stress properties of fabrics, the KES-F is seen as an effective research comparison tool but not appropriate for everyday industrial use due to its complexity and expense (31).

Since the development of the KES-F, efforts to objectively measure fabric handle have gone in two directions. One is the development of more simplistic objective measurement methods, and the other is efforts to increase the understanding of relationships between hand qualities that have been judged using subjective assessment, objective methods, and through the testing of hand-related standard mechanical properties (16).

An example of research relating to the second set of objectives was performed by Kim. An investigation of the physical properties related to the mechanics of fabric hand was performed. Woven fabrics were tested instrumentally against twenty different physical parameters. Samples were then tested using subjective assessment by a paired comparison method. Fourteen of these parameters showed good to average correlation between the objective and subjective testing and thus were chosen as component hand parameters. This research included a method for graphically representing values generated from the objective testing for each of the fourteen parameters (15).

2.3.1 Kawabata Evaluation System

The Japanese researchers Kawabata and Niwa are credited with the first instrumentation designed to measure the low stress mechanical properties of fabric. Low stress testing means that test specimens are not broken in runs. This began in 1972, when the Textile Machinery Society of Japan began an attempt to standardize the concepts and terminology used to describe and evaluate fabric handle. This initiative was part of a larger program to develop an objective measurement system for commercial use in the fabric and garment manufacturing industries in Japan. Based on this need, the Hand Evaluation and Standardization Committee (HESC) was formed under Professor S. Kawabata, as a way to bring order to the evaluation, measurement, and use of hand terms (7). The main purpose of this group of experts from the Japanese finishing industry was semantic definition. The HESC was to decide which descriptive terms best portrayed subjective aspects of hand for a specified fabric end-use (8).

The effort began with an assessment by an expert panel of subjective evaluators. The method of evaluation used by twelve experts from the wool weaving and finishing industries was observed. The result was the identification of Primary Hand Values (PHVs). Each PHV described the expert assessment of a specific hand characteristic. After judging the PHVs for a particular fabric type, the committee decided on an evaluation of the overall hand, or Total Hand Value (THV). The THV was based on a complex mental summation of these primary values in a two-stage process.

Standard fabrics were then chosen to represent and describe the PHVs. These standards were available for sale in book form. The next stage was then to objectively measure these samples, in terms of their mechanical, surface, and physical properties. The major driver of this research was to improve technical and commercial communication about fabric hand within the Japanese textile industry (7).

The instruments making up the KES-F system were manufactured by Kato Tech Co. of Kyoto. There are four instruments in the KES-F set, one measuring both tensile and shear properties, one fabric pure bending, one lateral compression, and one the surface characteristics of a fabric. The system was meant to quantify as many mechanical properties as possible. Six different properties or hand variables are covered in the testing and the calculated output is 27 measurements. However, this number is reduced to 16 parameters by the averaging of warp and fill (weft) directional samples (31). Block regression analysis is the statistical methodology used by Kawabata. A snake plot was also developed to visually display the results, using normalized results based on mean and standard deviation (7).

Kawabata's methodology assumes that fabric hand is derived from a combination of primary sensory factors such as softness, stiffness, and roughness. A second assumption is that the ultimate judgment of hand is dependent on the end-use. The unique feature of Kawabata's devices lies in their ability to measure fabric at small strains, and to characterize energy loss in mechanical deformation and the recovery process (7).

The first machines were released by Kato Tech in 1972. A later model, the KES-FB series was released in 1978, and designed to reduce the time for specimen preparation and testing. A more automated model, the KESFB-AUTO-A System, was released in 1997, equipped with automated sample loading procedures (7).

The KES-F system is a comprehensive testing system, however, its sophisticated structure and functions lead it to be an expensive endeavor. Additionally, the numbers of parameters that are given are not necessary for routine evaluations of textile products (11). The main end-use intended for Kawabata evaluation were suiting fabrics, and therefore samples do not exist for all types of textile products. Still, the strength of the Kawabata Evaluation System lies in its thorough analysis of fabric properties at low stress, and thus, if available, it could serve as an appropriate calibration tool for simpler objective test methods.

2.3.2 FAST System

The FAST system was designed by the Commonwealth Scientific and Industrial Research Organization of Australia (CSIRO) as a system for measuring fabric properties at low stress (11). These low stresses were created to simulate the type of stresses that fabric would be subjected to in the process of garment making (10). FAST was originally intended to act as a system to predict the tailorability of worsted fabrics. Today it is frequently used as a quality assurance tool in the woolen and worsted industries (31). The FAST system consists of three simple instruments for testing fabric mechanical properties and a test method for determining dimensional stability.

2.3.2.1 FAST-1 Compression Meter

CSIRO developed an instrumental test to measure the compression and surface layer properties of fabrics, and also to observe how stable these properties are to the rigors of finishing processes. In terms of worsted processing, pressing operations increase fabric compression, and decatizing serves to stabilize this compressed form. These in turn can affect the thickness of the fabric surface layer, and thus the appearance and hand of a fabric. Thus a test was developed to measure thickness, and also the variability and durability of the surface layer (23).

FAST-1 measures the thickness of a fabric under two fixed loads, T2 (2 gf/cm^2) and T100 (100 gf/cm^2). The difference in fabric thickness at the two loads is defined as fabric surface thickness, and this gives information about the bulk or the hairiness of a particular fabric (14). Figure 1 is a visual description of this fabric property.

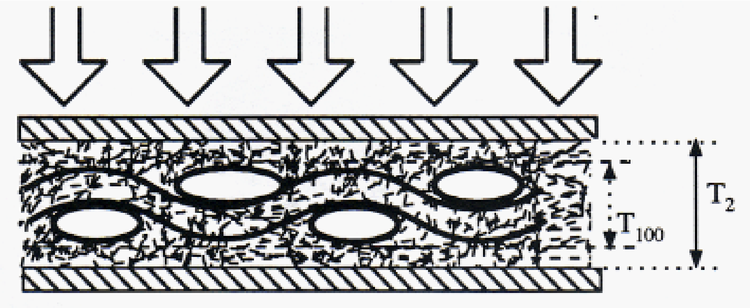


Figure 1: FAST-1 Thickness Measurement (14)

FAST-1 is used to measure the variability in fabric surface thickness, as well as a fabric's released surface thickness. The released surface thickness is often a measure of the stability of a fabric finish. The surface layer is measured before and after the fabric is subjected to steam, as this is indicative of what would occur during garment manufacture (23). Generally, a greater variation in surface thickness can be tolerated with thick fabrics than with thin fabrics. The FAST manual states that an increase in surface thickness by 1 mm can be felt and seen for some fabrics (4).

FAST-1 is performed by placing a fabric sample on the flat reference surface of the instrument. An object cup which contains the appropriate weight is then lowered carefully onto the fabric by turning the ring anti-clockwise until it stops (See Figure 2). The thickness reading at that load is then recorded after the displayed value has stabilized. An audible beep is heard by the operator, instructing them that the measurement has been recorded and to move on to the next placement. Next, the second weight is placed on the fabric sample, and the run is repeated (4).

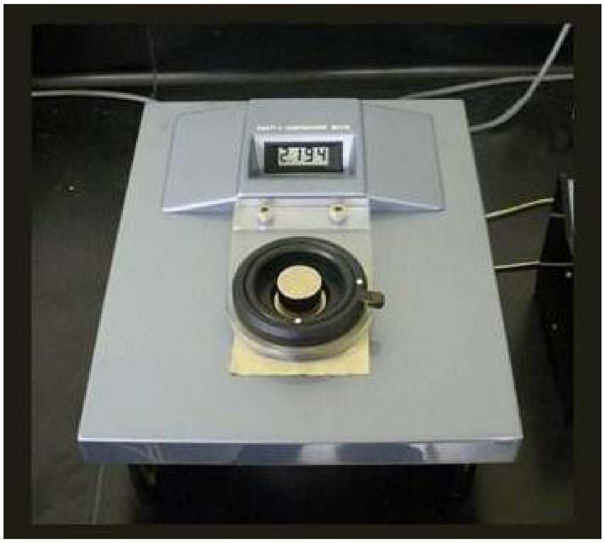


Figure 2: FAST-1 Instrument

CALCULATIONS: (4)

SURFACE THICKNESS, ST, in mm $ST = T_2 – T_{100}$

RELEASED SURFACE THICKNESS, STR, in mm $STR = T_2R – T_{100}R$

2.3.2.2 FAST-2 Bending Meter

FAST-2 measures two bending properties of a fabric, fabric bending length and fabric bending rigidity. Bending length is related to the ability of a fabric to drape, and bending rigidity is related more to the quality of stiffness felt when the fabric is touched or handled (23).

FAST-2 is a bending meter which works on the cantilever principle, meaning a fabric strip is pushed over a vertical edge until it has bent under its own weight to a specified angle, in this case 41.5° from the horizontal. The instrument uses photocells to detect the edge of the fabric and the bending length; thus calculating the bending rigidity based on the bending length and the fabric weight (4). Figure 3 depicts this principle:

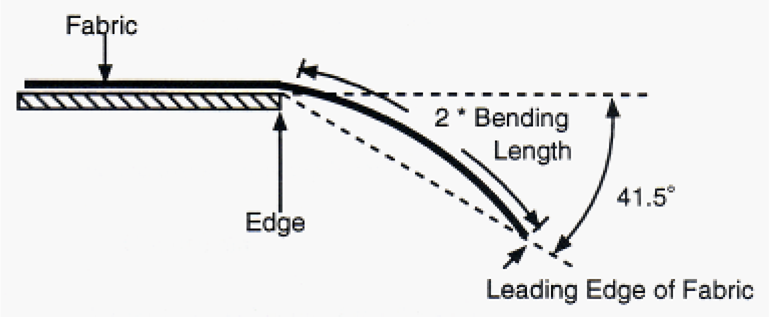


Figure 3: FAST-2 Cantilever Bending (4)

The FAST instrument totally encloses the electronics that it houses, leaving a smooth upper surface. A fabric strip is positioned on this smooth surface and an aluminum platen is placed on top of the specimen, leaving room on the leading edge of the specimen. The strip and the platen are pushed by the operator, until the leading edge of the specimen is pushed over the edge of the cavity and allowed to drape (See Figure 4). At this point, the specimen is detected by the photocells, initiating the measurement. Once the specimen cuts a beam of light set to 41.5°, a measurement is recorded and an audible beep is heard by the operator.

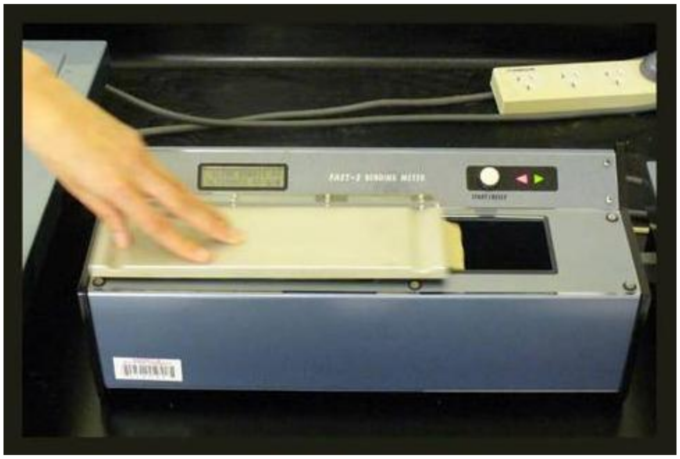


Figure 4: FAST-2 Instrument

Values for Bending Rigidity can be combined with FAST-3 extension results to obtain a measure of fabric formability. Fabric formability in this test method is related to the potential for seam pucker.

CALCULATIONS: (4)

BENDING RIGIDITY, B, in μN.m $B = W * c^3 * k$

Values required:

- Mass per unit area, W, in g/m^2
- Bending Length, c, in mm
- Conversion factor, k, = 9.81 x 10^{-6}

2.3.2.3 FAST-3 Extension Meter

The ability of a fabric to stretch or give at low loads is critical to garment and other sewn products' making-up procedures. FAST-3 is an extensibility meter, providing a direct measure of fabric extension under selected loads. Warp, weft and bias directions are tested on woven fabrics strips. Warp and weft strips are subjected to three loads (5, 20, and 100 gf/cm). Bias strips are used to calculate shear rigidity and are subjected to only 5 gf/cm load (4).

The ability of a two-dimensional fabric to form a three-dimensional product is related to the ability of the fabric to be sheared in its plane. This is characterized by shear rigidity, a parameter derived from bias extensibility. Fabric formability is another derived parameter, relating to values for extensibility at two loads and bending rigidity. This parameter was introduced by the work of Lindberg et al., and it is used to mean the amount of compression that is allowed by a fabric in a certain direction before the fabric starts to buckle. As a tailoring parameter, it related to the amount of overfeed possible in eased seams (sleeve cap, neckline) (23).

In the testing, specimens are gripped between two parallel sets of jaws and extended by any of three different loads. These loads are 5, 20, or 100 gf/cm. The instrument then measures the new gauge length of the jaws and the extension is described as a percentage. Figure 5 shows the movement:

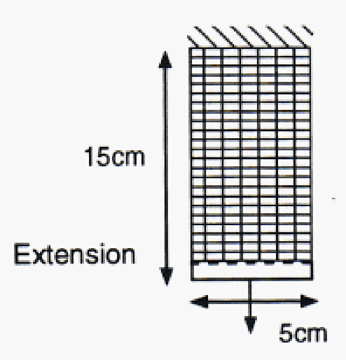


Figure 5: FAST-3 Extension

The instrument shown in Figure 6 uses a balance principle, with only the bottom jaw moving as a result of the loads. The removable weights are supported on the opposite end of the balance arm from the specimen. As the test progresses weights are removed from the balance arm, and when the locking knob is released, specimens are subjected to a greater gravitational pulling force. The gauge length is monitored by sensors, and when an audible beep is heard, extension is displayed as a percentage of fabric extension (4).

Figure 6: FAST-3 Instrument

CALCULATIONS: (4)

EXTENSION, %

- Calculate by the average values for a specimen in the warp and weft direction at specific weight loads

BIAS EXTENSION, EB5, %

- The average of all of the bias samples at 5 gf / cm

SHEAR RIGIDITY, G, in N/m $G = 123 \div EB5$

Values required:

- Bias extension, EB5, in %

FORMABILITY, F, in mm^2 $F = ((E20 - E5) * B) \div 14.7$

Values required:

- Extension at 5 gf/cm, E5, in %
- Extension at 20 gf/cm, E20, in %
- Bending Rigidity, B, in μN.m

2.3.2.4 FAST-4 Dimensional Stability

Poor dimensional stability has a negative impact on the final appearance of textile products, including size changes, poor matching of seams, and puckering. Atmospheric changes or steaming can cause hygral expansion or relaxation shrinkage. Hygral expansion or contraction is caused by the swelling or deswelling of hygroscopic fibers in atmospheres of changing humidity. Relaxation shrinkage is due to the recovery of fibers strained during manufacturing processes (23). Some relaxation shrinkage is necessary, for reducing bulk in eased seams (armholes etc.), though high levels cause problems.

FAST-4 consists of a test method rather than a specialized instrument. The test uses an oven and consists of a cycling series of drying and wetting stages. After each of these stages, fabric dimensions are recorded in both warp and weft directions. Two properties are calculated from this method, relaxation shrinkage and hygral expansion (10).

The procedure is as follows:

Three pairs of reference points are made on 30 cm x 30 cm specimens in both the warp and weft directions using a template. Marks are made with a Texpen, similar to liquid paper. Fabric specimens are placed on racks in a laboratory convection oven for 1 hour at 105°C. Changes in the distance between warp and weft dots on the fabric are measured within 30 seconds of taking a sample out of the oven. These provide the initial measurements, L1.

Samples are then soaked in a solution of water (25-30°C) and 1% wetting agent for 30 minutes. Samples are taken out of the water, placed on flat surface, blotted with a towel, and re-measured. These provide the second set of measurements, L2.

Samples are then placed in the oven for 1 hour at 105°C for a second time. Fabrics are taken out and measured for the last time, providing measurements L3. To calculate the results, the averages were taken for each sample's L1, L2, and L3 values, for both warp and fill.

CALCULATIONS: (4)

RELAXATION SHRINKAGE, RS, % $RS = 100\,(L1-L3) \div L1$ (%)

HYGRAL EXPANSION, HE, % $HE = 100\,(L2-L3) \div L3$ (%)

2.3.2.5 FAST Output Plot

The main output of FAST is a control chart that specifies upper and lower acceptable limits for each fabric property. The actual values of the fabric are plotted and a line connects the values to generate what is called a snake plot.

(31). The existing FAST Control Chart, showing a plot for one fabric, is shown in Figure 7:

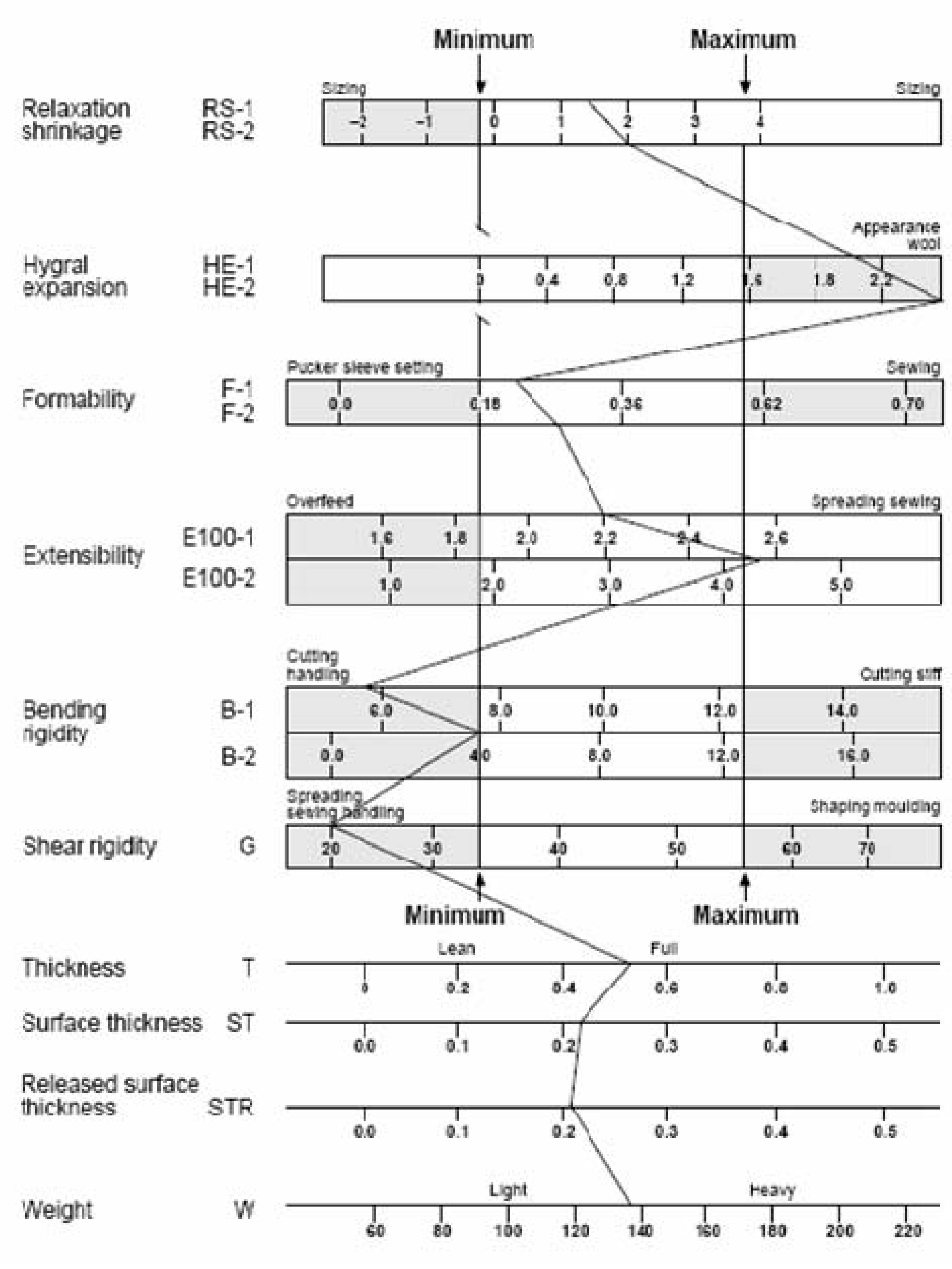


Figure 7: FAST Control Chart

The primary purpose of the FAST system was to provide an affordable and simplified test method for the garment and finishing industries, much of which could not justify the expense of KES-F. However, there has been interest in the

FAST system as a tool for generating fabric hand values, and the following research is related to that area of interest.

Work by Thompson evaluated the FAST system as a measurement of fabric mechanical properties. The purpose was to see whether these measurements provided by the FAST equipment provided an accurate assessment of fabric hand. Results found that the FAST system compares favorably with the KES-F system. The KES-F system generated more detailed information; however the FAST system was shown to be effective in measuring mechanical properties and their relation to fabric hand. Suggestions were made that the speed and relative affordability of the FAST system lends them to be effective for use in conjunction with the KES-F system or on their own for companies not able to afford the KES-F system (32).

Work by Jain studied the applicability of the FAST system in testing nonwovens used in apparel. As FAST was originally developed for woven fabrics, efforts were made to develop a methodology for modifying the limits of the FAST control chart for nonwovens. A result of this research is a methodology for the development of fingerprint charts for different textile applications. The research involved the development of software for the modification of the FAST fingerprint chart. Software allowed for fabric weight registration, the operator to determine the absolute limits and unacceptable zones for the fingerprint chart, and the superimposition of different fabrics by style lines on the plot (14).

Research by Mazzuchetti and Demichelis also investigated the use of the FAST equipment for predicting fabric hand, this time on wool and wool/blend suiting fabrics. Of primary interest were the feelings of coolness and dryness experienced when touching fabric. Numerical values from the testing of mechanical properties on FAST equipment were compared to subjective analysis in the form of a panel of expert judges. This follows the method developed by Kawabata and others for the standardization of primary hand. Results from the objective and subjective testing were analyzed using multiple linear regressions with a comparison of three mathematical models. The output showed a strong correlation, pointing to the use of FAST equipment as a method of predicting fabric hand. Finally, it was found that the following parameters were most correlated with the subjective impressions of coolness and dryness: superficial thickness, bending rigidity, and weight (21).

2.3.3 Pull-Through Methods

Pull-Through testing is a simple and practical method for achieving information about fabric handle. Researchers believe this method to closely approximate the fabric tactile response a human experiences when touching and grabbing a fabric. The act of pulling fabric through a ring to test for softness was performed by ladies purchasing silks in the middle ages in Europe (13). The ease with which the fabric could be pulled provided information with which quick comparisons could be made in the marketplace. There are also historical writings relating that extremely fine hand-woven muslin could be folded so compactly that it could be packed into a matchbox (13).

Recently, the physical deformations associated with fabric passage through a ring or orifice has been used to generate information relating to fabric handle. As the fabric passes through, it gets folded, sheared, bent, compressed, and rubbed against the interior wall of the orifice during withdrawal (13). This withdrawal force can then be recorded using the load-elongation chart generated by the tensile testing machine. The initial deformation of the fabric is related to the properties of bending modulus and the shear stiffness of the fabric. Compression properties come into play as the fabric is squeezed to the dimensions of the ring. Other forces that affect the withdrawal force are fabric friction with the inner surface of the orifice and the extensibility of the fabric (13).

Alley obtained a patent in 1979 for the first such pull-through, or extraction, device for objectively measuring fabric hand. This method used a nozzle composed of a truncated cone section and an annulus section. This was mounted on a tensile testing device (6).

This nozzle with a half-cone shape was also used by Behery, as well as Pan and Yen. Behery's research included comparisons of fabric using a variety of test methods. Test methods included nozzle pull-through (based on Alley's patented method), KES-F system testing, a range of simple physical lab tests, and a subjective panel. Pull-through results were shown to have good correlation with KES-F results (8).

Pan and Yen attempted to interpret the curve generated by a fabric as it passes through the nozzle. Points on the curve were identified as representative of specific mechanical properties, and connections were made between these points and the sixteen fabric mechanical properties measured by the KES-F system. Conclusions of the test were that the pull-through method can be used to generate data for multiple fabric properties using one test (24).

Kim and Slaten used a nozzle pull-through technique to measure the effects of flame retardant finishes on fabric hand. The pull-through method was found to be able to differentiate between a range of flame retardants on the same fabric based on their frictional characteristics. It was also found that frictional forces were more pronounced in fabrics exhibiting a low level of drape. It was found that the flame retardants varied in their effect on hand; some imparted a harsher and stiffer hand to the fabric, while others decreased these as compared to the greige fabric (17).

Grover developed a similar apparatus; however, instead of pulling fabric through a nozzle, he used a ring shape. This study was a comparison of woven shirting fabrics and consisted of an analysis of the effects of different functional finishes on fabric handle. The overall handle force was shown to increase with heavier and stiffer fabrics. Also, the correlation between shear stiffness and handle force was high. Information gathered from the application of various softener treatments and launderings showed a correlation with coefficient of friction, work of compression, and fabric weight. Researchers warned that this method requires a large sample size as a high degree of variation exists in the handle force measurements. This is due to the folding configuration of the fabric as it passes through the ring (13).

Research by Steckert used a ring pull-through device that is attached to an Instron tensile tester to obtain quantitative estimates of fabric hand. The Instron pulled fabrics through a variety of different ring diameters at different speeds. Resulting values were compared to values generated for the same fabrics on Kawabata KES-F systems and through subjective paired-comparison analysis. Tests were conducted on both knit and woven fabrics. Results showed that softness, smoothness, stiffness, and overall hand values from the ring pull-through method, the KES-F system, and the subjective paired comparison were correlated for knit fabrics as they relate to fabric hand. It was found that stiffness values for woven fabrics were correlated. Therefore a conclusion of this research was that the ring pull-through method is an effective tool for quantitatively measuring the hand of knit fabrics (30).

More work by Kim & Slaten used a ring pull-through apparatus to measure the change in hand resulting from different fabric types (all woven), flame retardant finishes, and fabric wetness. The hand-related properties drapeability, flexural rigidity, and static friction resistance were the important factors related to the force required to pull the fabric through the metal ring. Drapeability and foldability were found to be the most significant property related to pull-through force (16).

Researchers believe pull-through methods to be more effective than other objective techniques at simulating the overall impressions of fabric hand that would be experienced by a consumer. Pull-through methods allow one to quantify the interaction between properties, as opposed to other methods (FAST, KES-F) that test properties independently (16).

2.4 Conclusions of Review

The Kawabata Evaluation System is known as the most complete method for evaluating fabric hand and comfort characteristics. It is a system for assigning fabrics specific values for handle parameters. However, the breadth of information, time, and expense is generally not appropriate for routine quality control and product development trials. Additionally, the interpretation of the results of the KES-F system can be muddy in terms of how to correlate the tested mechanical properties with overall hand values.

Another issue is that KES-F hand parameters are calculated using equations developed for specific end-uses (12). For new-to-the-world products or for products being updated with the latest functional requirements, it is needless to develop new equations. Rather it is important for companies to make decisions on parameter priorities and then assign rankings to fabrics based on quick test methods.

The FAST system was developed to overcome some of the shortcomings of the Kawabata Evaluation System. Specifically designed for the wool industry, FAST is mainly used in garment-making and finishing to assess tailorability. The simplicity of the FAST system has led researchers to investigate it as a tool for generating fabric hand values. The output of FAST, a control chart in the form of a snake plot, lends the tests to be used as a quality assurance tool, not just for garments but also for other textile products. The tests are quick to run (for both repetitions and replications) and the machinery is simple to operate and does not take up a lot of space. The output of FAST is more complete than the pull-through method but easier to interpret than the KES-F. Some of the FAST system tests are limited in terms of fabric types, however, as knits and other highly extensible fabrics are not appropriate for the FAST-3 extension test.

In contrast to KES-F and FAST, the pull-through method is simplistic in its evaluation of fabric handle. The fabric extraction method may not be precise in its assessment of all of the parameters relating to fabric handle, however, the summated force values can provide a user-friendly simple tool for comparing fabrics. The research shows that the extraction method can be adept at differentiating between comparable fabrics that have different handle characteristics (16, 27). The simplicity of the apparatus and test method lend it to be a potentially valuable tool for industry testing laboratories, where it could be used as a screening method during product development and quality control.

It is clear from the above that there has been a significant amount of research in the area of developing a “Fabric Hand Matrix”; however this seems to have been restricted to Academia. While Kawabata may be regarded as a standard, it has found little acceptance in industry due to its very high cost and complexity. FAST seems a likely lower cost alternative to KES-F, however its use has been restricted to wool processes. This is either due to possible unreported limitations in the system, or more likely to poor marketing strategy. The industry is thus still without a low cost, reproducible test method of sufficient sensitivity to reflect changes that can be detected by subjective evaluations.

The purpose of the present research is to re-examine the most likely candidate for this role, which is the Ring Pull-Through tester. Data generated from this method will be correlated with all tests to determine whether this can indeed be adopted as a simple test by the industry, both in the research and in the manufacturing setting.

CHAPTER III

3 Methodology

The main purpose of this research is to develop the CSIRO FAST System and the Ring Pull-Through Method as tools for hand evaluation. To this end, fabric samples were tested using the following methods: (a) a subjective rank-ordered comparison, (b) Fabric Assurance by Simple Testing (FAST), and (c) Ring Pull-Through (RPT). A statistical analysis was then performed to establish a correlation between fabric hand values measured using the Ring Pull-Through and those of commercial methods, and finally to compare results from the objective test methods to the subjective evaluation.

3.1 Collection of Sample Fabrics

Fabrics were obtained from three ITT member companies. Collected fabrics were limited to wovens. Sample fabrics are shown in Table 1:

Table 1: Acquired Fabrics

Type	Style	End Use	Construction	Fiber	Finish	Wt. (g/m^2)
A	A1	Suiting	Woven	Worsted	Control	175
	A2				Warp Stretch	182.5
	A3				Softener 1	177.5
	A4				Warp Stretch + Softener 1	177.5
	A5				Softener 2	182.5
	A6				Softener 1 + Softener 2	176.7
	A7				Water/ Oil Repel	175
	A8				W/O Repel + Softener 1	172.5
	A9				Easy Care	182.5
B	B1	Suiting	Woven	Worsted	Control	170
	B2				Warp Stretch	176.25
	B3				Warp Stretch + Softener 1	173.75
	B4				Softener 2	176.25
	B5				Softener 1 + Softener 2	172.5
	B6				Water/ Oil Repel	171.25
	B7				W/O Repel + Softener 1	170
	B8				Easy Care	173.75
C	C1	Camo	Cordura	Nylon	Dye	156.7
	C2				Print	158.3
	C3				DWR	156.7
D	D1	Camo	Woven Stretch	Nylon	Dye	152.5
	D2				Print	145.8
	D3				DWR	145
E	E1	Napery	Plain Weave	Synthetic	Prepared	200
	E2				Multiple Finish	202.5
F	F1	Denim	Twill	Cotton	Prepared	305
	F2				Mercerized	335
	F3				Heat Set	336.25
	F4				Sanforized	385

All fabrics were woven for an apparel end-use except for E, the napery fabrics. Woven fabrics were requested as we feel that the hand and comfort of knitted fabrics is due to a simpler set of variables, such as fiber diameter. Requested were fabrics that showed a base fabric with a range of finishing treatments or processing conditions, so that an incremental change in hand could be observed. In general, three yards were obtained for each style.

3.2 Subjective Hand Evaluation

A subjective hand evaluation was performed at North Carolina State University. The following are the steps of this method of evaluation:

- Sample Preparation
- Choice of Respondents
- Choice of Descriptors
- Questionnaire
- Conducting the Survey
- Statistical Analysis of Data

3.2.1 Sample Preparation

Fabric samples used in the testing were cut to 11.75” x 11.75” (30cm x 30cm) squares. Fabrics were cut using pinking shears so as to reduce fraying without the edge roughness associated with stitching and serging. Once cut, the fabrics were folded over once (face side out) and clipped onto small wooden trouser hangers. During testing, hangers were hung from a metal bar parallel to the floor.

3.2.2 Choice of Respondents

Respondents were limited to university students. Testing was conducted in Rm. 1121 of the College of Textiles at North Carolina State University. Demographic information for the respondents is given in Table 2:

Table 2: Age, Ethnicity, and Gender Distribution of Evaluators

Demographic	Count
Age Range	19-36
Gender	
Male	8
Female	8
Nation of Origin	
USA	11
Bolivia	1
India	1
Iran	1
Korea	1
Thailand	1

3.2.3 Choice of Descriptors

Hand-related descriptors for evaluation by the judges were chosen to correspond with tests from FAST and Kawabata. Each hand-related term was given a pair of polar adjectives, to aid the evaluators in differentiating between samples based on a category. The following are descriptors and their corresponding adjectives:

COMPRESSIBILITY: Firm ↔ Soft
EXTENSIBILITY: Stretchy ↔ Not Stretchy
BENDING: Stiff ↔ Pliable
SURFACE: Smooth ↔ Rough

The next step was to acquire fabrics that were representative of these polar adjectives. Store-bought samples were used as an educational tool in the initial instruction of the judge, and then to provide extremes during the rank ordering of samples during the testing. Table 3 is a description of the included fabrics:

Table 3: Subjective Grouping Descriptors and Controls

Descriptor	Polar Standard 1	Polar Standard 2
Compression	Coated Plain Weave	Cushioned Composite
Extension	Cotton Duck	Stretch Denim
Bending	Coated Plain Weave	Sheer Plain Weave
Surface	Burlap	Satin
Controls	**Control 1**	**Control 2**
Style	D1	C3

3.2.4 Questionnaire

A questionnaire was designed to be filled out by the test proctor during the administration of the test. The first page of the questionnaire consists of personal information. The questionnaire used for the survey is shown below. The questionnaire shows the rating scale for just one of the fabric types used in this research.

A SURVEY ON SUBJECTIVE ASSESSMENT OF FABRIC HAND

Name

____

What is your Age?

____

Gender

______ Male
______ Female

What is your Nationality? (E.g., American, Korean, Indian etc)

____

Are you willing to repeat this test in the near future to help validate your results?

______ Yes

______ No, thanks

THANK YOU FOR PARTICIPATING IN MY RESEARCH!

RANK ALL SAMPLES BASED ON POLAR ADJECTIVES

FABRIC A: Men’s Suiting

←Firm COMPRESSION Soft→

←Not Stretchy EXTENSION Stretchy→

←Stiff BENDING Pliable→

←Rough SURFACE Smooth→

←Least PREFERRED FOR END USE Most→

←Least COMFORTABLE FOR END USE Most→

3.2.5 Conducting the Survey

Tests were conducted with only one evaluator at a time. Observers washed their hands and were then seated in front of the hanging device. Observers were given a brief explanation for the textile descriptors (compression, extension, bending and surface) and were handed swatches of the two polar fabrics for each extreme so as to educate them on the qualities that they would be rating during the test.

The subject then put on blackout goggles so as to eliminate visual bias. The first sample grouping was placed on hangers and these were hung in random order on the hanging device. Each sample grouping consisted of all of the styles within a fabric type, plus the inclusion of the two polar adjective samples for the selected descriptor. Additionally, two fabrics that were used as constants were included in each grouping, these being a specimen each from fabric style codes C3 and D1.

For the fabric shown in the above questionnaire, Fabric A, the sample grouping was made up of the 9 styles of this suiting fabric, plus the 2 polars that changed according to which descriptor was being rated for, plus the C3 and D1 constants. This is a total of 13 hung fabrics on the hanging device, the largest sample grouping.

The subjects were given a descriptor (e.g., compression) and told to rank-order the hangers in relation to the two poles of the descriptor, corresponding to the two ends of the hanger device bar. Respondents were allowed to say “no detectable difference” between fabrics within a sample grouping. Once the evaluator had finished, the order of the fabrics was marked on the questionnaire by the proctor.

The two previous descriptor polars were then replaced by the polars for the next descriptor. The subject reordered the fabrics according to the new descriptor. This was done until all four descriptors had been used for a sample set. In the final two questions, test subjects were asked to rate fabrics based on personal preferences for end use and comfort. No descriptor polar fabrics were included in this order. A new sample grouping was then placed randomly on the hanger device and the same analysis was performed. Figure 8 shows a subjective evaluation in progress.

Figure 8: Subjective Hand Evaluation Trial

3.3 FAST System

FAST testing was performed at North Carolina State University. The following are the steps of this method of evaluation:

- Sample Preparation
- Instrumental Testing
- Modified Output

3.3.1 Sample Preparation

Samples were cut using plexiglass templates as guides for a circular knife. Samples were cut on a fabric cutting board across the width of the fabric. The template placement is shown in Figure 9, with the 30 x 30 cm template in the middle of the fabric width, and the 20 x 20 cm template being used to cut four pieces, 2 being square and in the warp direction and two diamonds in the bias (45 degree angle) direction. The 30 x 30 cm square was used as the FAST-4 Dimensional Stability sample. Cut shapes were marked with arrows in the warp direction. A triangular template was used to line up the square 20 cm template for cutting in the bias direction. Cut edges were kept at least 5 cm from the selvages.

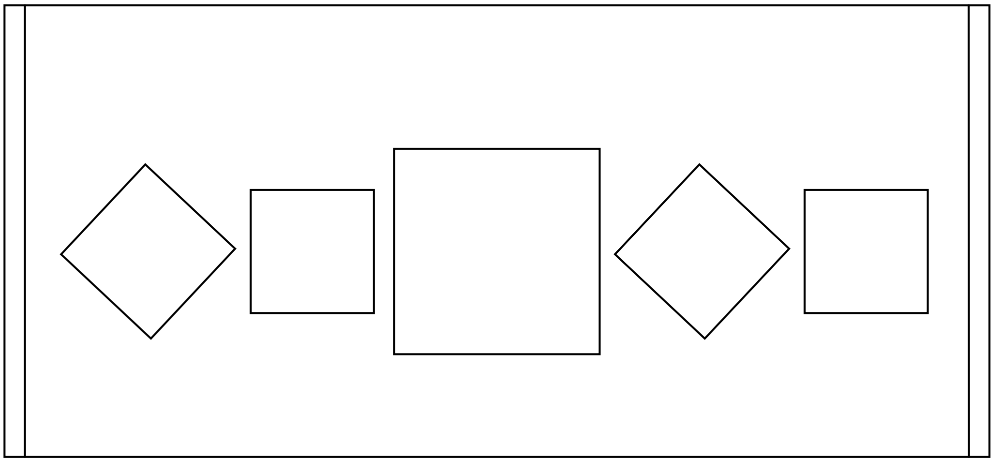


Figure 9: CSIRO FAST Template Placement

Figures 10 and 11 show the templates used for cutting FAST-1, FAST-2 and FAST-3 samples. Each square generates two warp strips, two weft strips, and a square FAST-1 compression sample. Each diamond generates two right-hand bias and two left-hand bias strips, and a FAST-1 100mm x 100mm compression sample. FAST-2 Bending Meter uses the 50mm x 150 mm samples cut parallel to the warp or the weft direction. FAST-3 Extension Meter uses 50 mm x 150 mm samples cut parallel to the warp or the weft direction and also bias-cut strips, both left and right-handed. Arrows indicate how samples were marked with a Texpen.

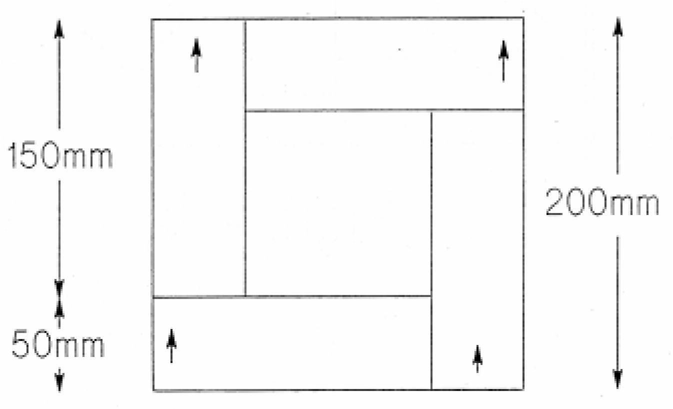


Figure 10: Square Sample Cutting Method

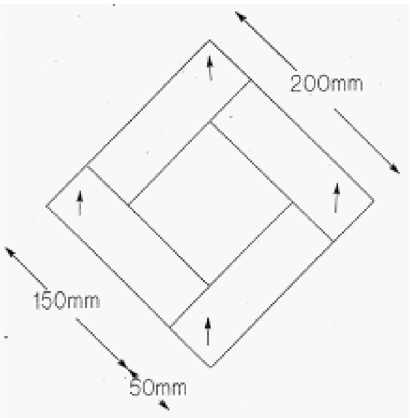


Figure 11: Diamond Sample Cutting Method

Samples for FAST-1, FAST-2, and FAST-3 were conditioned in the lab for 24 hours prior to testing at standard conditions (20˚C, 65% RH).

3.3.2 Instrumental Testing

Instrumental testing for FAST-1, FAST-2, and FAST-3 was performed in room 1311 at North Carolina State University. All tests were performed for all styles of fabrics used in this research. The FAST-1, FAST-2, and FAST-3 instruments are shown in order from left to right in Figure 12.

Figure 12: CSIRO FAST Instruments

For each style of a particular fabric type, five FAST-1 readings for 2 gf/cm^2 and five readings for 100 gf/cm^2 were taken using four 100 mm x 100 mm samples. Each of the four samples was tested at both of the compression levels, with one sample having two differently placed readings for each weight.

FAST-1 involves the testing of samples in two stages. After testing fabric samples using both weight levels, they were retested as part of the test for Release Surface Thickness. For this test, fabrics were exposed to steam for 30 seconds and then vacuumed for 20 seconds using a Hoffman open bed press in the Apparel Lab at the College of Textiles. These same four samples were then retested at both compression levels giving a total of 20 readings per style.

FAST-2 bending testing was performed on 50 mm x 150 mm samples. Four warp direction and four weft direction samples were tested. Each of these samples was tested twice, once on the front, or the face of the fabric, and once on the back. A total of 16 readings per style were taken.

FAST-3 extension testing was performed on 50 mm x 150 mm samples as well. Readings were taken on three warp, three weft, and six bias samples. The extensibility of the warp and weft samples was measured at loads of 5, 20 and 100 gf/cm. Bias strips were measured at only the 5 gf/cm weight. A total of 24 readings per style were taken. The 50 mm x 150 mm warp and weft direction samples underwent this test after the FAST-2, so as to move from least deformation to most deformation through the course of the testing.

FAST-4, a test for relaxation shrinkage and hygral expansion, was performed in the Pilot Plant at North Carolina State using a Yamato Mechanical Convection Oven. For the wetting-out procedure, samples were immersed in a solution of water and 1 gram per liter Primasol NSA wetting agent. One 30 x 30 cm sample was tested for each fabric style.

3.3.3 Output

Raw data from the FAST testing was organized into a formatted Microsoft Excel spreadsheet for plotting in Excel and JMP statistical software. Table 4 lists and defines the 25 output variables of FAST testing.

Table 4: FAST Output Variables

VARIABLE	UNITS	MEANING	CALCULATION
Dimensional Stability			
RS-1	(%)	Warp Relaxation Shrinkage	100 (L1-L3) / L1
RS-2	(%)	Weft Relaxation Shrinkage	101 (L1-L3) / L1
HE-1	(%)	Warp Hygral Expansion	100 (L2-L3) / L3
HE-2	(%)	Weft Hygral Expansion	101 (L2-L3) / L3
Extension			
E5-1	(%)	Warp Extension	% at 5 gf/cm load
E5-2	(%)	Weft Extension	% at 5 gf/cm load
E20-1	(%)	Warp Extension	% at 20 gf/cm load
E20-2	(%)	Weft Extension	% at 20 gf/cm load
E100-1	(%)	Warp Extension	% at 100 gf/cm load
E100-2	(%)	Weft Extension	% at 100 gf/cm load
EB5	(%)	Bias Extensibility	% at 5 gf/cm load
Bending			
C-1	(mm)	Warp Bending Length	Automatic
C-2	(mm)	Weft Bending Length	Automatic
B-1	(µN.m)	Warp Bending Rigidity	W x c^3 x *k*
B-2	(µN.m)	Weft Bending Rigidity	W x c^3 x *k*
Shear			
G	(N/m)	Shear Rigidity	G = 123 / EB5
Formability			
F-1	(mm^2)	Warp Formability	(E20 – E5) x B) / 14.7
F-2	(mm^2)	Weft Formability	(E20 – E5) x B) / 14.8
Compression			
T2	(mm)	Thickness	mm at 2 gf/cm^2
T100	(mm)	Thickness	mm at 100 gf/cm^3
ST	(mm)	Surface Thickness	T2-T100
T2R	(mm)	Released Thickness	mm at 2 gf/cm^2
T100R	(mm)	Released Thickness	mm at 100 gf/cm^3
STR	(mm)	Released Surface Thickness	T2R-T100R
W	(g/m^2)	Weight	Digital Scale

3.4 Ring Pull-Through Testing

Pull-Through testing was performed at North Carolina State University. The following are the steps of this method of evaluation:

- Instrument Design
- Sample Preparation
- Instrumental Testing
- Output
- Trials

3.4.1 Instrument Design

The Ring Pull-Through method used in this research is based on the method developed in 1993 by researchers Grover, Sultan, and Spivak (13) and more recently by Heidi Steckert in her 2003 thesis for ITT (30). This involves the use of a stand that mounts into the bottom attachment slot of a tensile testing machine as a device for pulling through fabric. In the case of this research, an MTS tensile tester was used. The Ring Pull-Through (RPT) device used in this research was constructed by Hai Bui in the Machinery Shop at the College of Textiles at NCSU.

In the design of a new apparatus for this research, some modifications were made to the pre-existing devices used by Grover and Steckert. Steckert's device used ring sizes of 2, 2.25 and 2.5 cm. To accommodate a greater range of fabrics, ring sizes of 2, 2.5, 3, and 4 cm were used in this research. Additionally, for each diameter, both a shallow ring and deeper cylinder were made, for a total of eight rings versus the previous three. To accommodate the larger ring sizes, the width of the top plate of the RPT device was expanded.

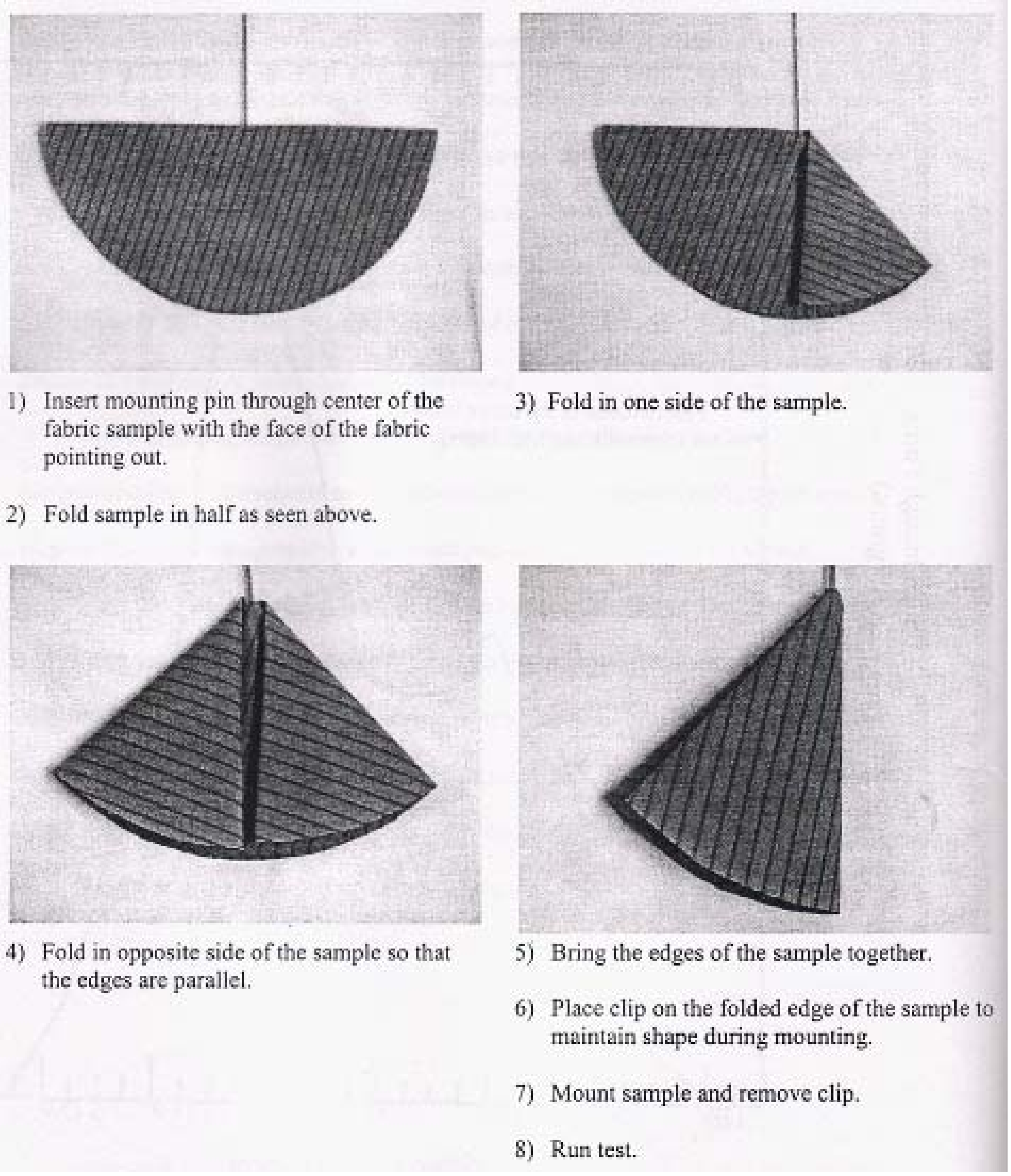
Further modifications were made to the mounting pin, which passes through the center of a fabric sample and is held by the upper jaw. This was used for pulling fabric samples through the ring. It was found that, given the 10N load cell that was used for this procedure, the use of the tensile tester upper jaw posed a weight problem. Given the available load cells of 1N, 10N, and 250N, it was necessary to reduce the load on the load cell if accurate measurements were to be taken. If a 25N load cell had been available, the use of jaws would not have been as much of a problem, and accurate measurements could still have been made. Therefore, a mounting pin attachment was developed that easily slid into, and was held by a pin, in the screwed base of the load cell. This also led to more consistent positioning of the mounting pin during runs, as the vertical alignment of the device was basically error-proofed.

The schematics of the RPT device used in this research are shown in Appendix C. The frame, plug and all rings were constructed out of aluminum. The mounting pin shaft, retainer ball, and mounting pin attachment were constructed out of stainless steel. Additionally, steel screws were used.

3.4.2 Sample Preparation

A 10 inch diameter circular template was created for cutting all samples, with the center hole marked. Holes were poked through the center dot of the circular samples using the end of the mounting pin. Samples were taken from all styles of the fabric types. Samples were taken from across the width of the fabric. Samples were stored loosely folded in half in plastic sleeves of thick binders. To prevent creasing and wrinkling, samples for a particular style were folded together to prevent sharp folded edges. Samples were conditioned in the Pull-Through Testing Laboratory for 24 hours prior to testing. During this time, samples were laid flat.

For pulling the fabric samples through the rings and cylinders, the folded mounting procedure adopted from Steckert's previous ITT research (30) was used for a majority of the testing. The sample folding and mounting procedure is shown in Figure 13:



1) Insert mounting pin through center of the fabric sample with the face of the fabric pointing out.

2) Fold sample in half as seen above.

3) Fold in one side of the sample.

4) Fold in opposite side of the sample so that the edges are parallel.

5) Bring the edges of the sample together.

6) Place clip on the folded edge of the sample to maintain shape during mounting.

7) Mount sample and remove clip.

8) Run test.

Figure 13: Sample Folding and Mounting Procedure (30)

An exception to this was the trials conducted to see the effect of this folded mounting procedure versus a more freeform procedure, Trial 5.

3.4.3 Instrumental Testing

Testworks 3.1 software was used to run the MTS tensile tester (Model 1122). Before beginning RPT testing, a new Testworks method was created. Key test inputs included the following parameters:

LOAD CELL

- 10N

LOAD LIMIT

- Based on load cell
- HI (7.5 N)
- LO (-7.5 N)

EXTENSION LIMIT

- Determines how far the crosshead moves during a run
- HI (14.5 cm for Normal Ring, 18 cm for Cylinder)
- LO (-1 cm for Normal Ring and Cylinder)

INITIAL CROSSHEAD POSITION

- Adjusted based on ring type used in run
- Screen ruler position reset to zero at beginning of run, however zero position for Cylinder is 3.5 cm lower than Normal Ring zero position

INITIAL SPEED

- Default (20 in/min or 50 cm/min)

SPECIFIED UNITS

- Converted to metric

After all of the above parameters were found to be correctly entered or saved based on fabric type and ring size and shape, testing for each specimen was as follows:

1) The fabric specimen is penetrated through the center mark with the sharp end of the mounting pin
2) The specimen is folded as shown in the sample folding and mounting procedure (Figure 13)
3) The mounting pin is inserted into the mounting pin attachment and screwed into position.
4) The top point of the folded sample, draped around the mounting pin retainer ball, is positioned in line with the lower rim of the ring.
5) The fabric is held in folded position until the operator tells the computer to run the test.
6) The test run begins and the sample is pulled upward through the ring.
7) The sample continues to move upward until the specified Extension Limit HI is exceeded. This is set so that the lower edge of the specimen hangs one cm above the top of the RPT device frame.
8) The operator tells the program to “File” the test run
9) The operator removes the mounting pin from the mounting pin attachment and then the crosshead moves back down to the starting position.
10) The operator at this point may run the same specimen by reinserting the mounting pin, run a different specimen on the mounting pin, or the operator may change out the ring for one with a different size or shape.

Figure 14 shows fabric D1 being pulled through the RPT device, in this case, before the mounting pin attachment was developed. Thus a grip is used.

Figure 14: Fabric D1 RPT Trial Run

3.4.4 Output

Testworks 3.1 software was configured to automatically measure and report peak load in grams. The load-displacement curve data points were also filed. This data was exported to Excel and plotted to show the change in the force required to draw a fabric specimen through a ring. Peak load is the maximum height of the load-displacement curve and this occurs after most of a fabric specimen has been pulled through the ring. Peak load can be set to be automatically reported by the software. This can provide a simple measurement for differentiation, with values for peak load mean, standard deviation, and coefficient of variation providing a basis for sample set comparison. This was the primary output variable for Steckert's RPT research (30).

Beyond peak load, the load-displacement curve for each specimen run was imported into Excel. General information can be gathered from the shape of the curve. Steckert found that ring diameters that were too small for a sample set did not allow the specimen to move through the ring smoothly, leading to inaccurate readings. Large diameter rings, however, generated flat curves with peak loads that were hard to distinguish (30). This information was used for assigning sample sets to their appropriate ring size, and also for studying the effect of the folding and mounting procedure.

This research also included the analysis of specimen runs via the area under the load-displacement curve. To find the area, it was important to begin by eliminating the noise on the tail ends of the curve. Next, using Excel spreadsheet functions, the area was found using a summation of the x and y rectangles of the curves. The midpoints between individual points of the curve were used. The summation of all of these rectangles rendered one area measurement per curve, expressed in grams*cm. This area measurement could then be analyzed for mean, standard deviation, and coefficient of variation similar to peak load.

3.4.5 Trials

The following trials, 1, 2, and 3 were run for all acquired fabric types, A through F. Trials 1, 2, and 3 compose a developed method for evaluating a new sample set of fabrics. The purpose of these trials is to determine the consistency of a new group of fabrics, the appropriate ring diameter for those same fabrics, and then finally to differentiate between varying styles of those fabrics (variations in chemical or mechanical finishing, processing conditions, etc).

TRIAL 1: REPETITION

- Pick one circular specimen for each Fabric Type (A,B,C,D,E,F)
- Run the specimen 20 times in a row in one session per ring diameter
- Begin with 4 cm ring and run specimen on all four ring diameter (no cylinders)
- Plot peak loads over the course of the 20 runs, showing this for all four ring diameters on the same plot
- Examine for trends

TRIAL 2: RING DIAMETER DOE

- Develop a Design of Experiment (DOE) with three factors (Ring Shape, Ring Diameter, and Fabric Type Styles).
  a) For fabric types A, B, and E, the design is 2 shapes x 4 diameters x 2 styles.
  b) For fabric types C, D and F, the design is 2 shapes x 4 diameters x 3 styles.
- Set up the DOE with one replicate (doubles the number of runs).
- Randomize the run order.
- Run for a fabric type at one speed for one session.
- Analyze peak load, area, and shape of the Load-Displacement Curves to determine the optimum ring diameter for a fabric type.

TRIAL 3: VARIATION BY FABRIC STYLE DOE

- Develop a Design of Experiment (DOE) with three factors (Ring Shape, Ring Diameter, and Fabric Type Styles).
  a) For fabric type A the design is 2 shapes x 1 diameter x 9 styles.
  b) For fabric type B the design is 2 shapes x 1 diameter x 8 styles.
  c) For fabric types C, D, F the design is 2 shapes x 1 diameter x 3 styles.
  d) For fabric type E the design is 2 shapes x 1 diameter x 2 styles.
- Set up the DOE with four replicates (total of five specimens per setting combination).
- Randomize the run order.
- Run for a fabric type at one speed for one session.
- Analyze peak load, area, and shape of the Load-Displacement Curves to analyze the variation between and within styles of a fabric type.

Trials 4 and 5 were performed with a purpose of developing the RPT procedure as a method for fabric evaluation. These trials were not performed for all fabric styles; however they both use select runs from the previous trials as a basis of comparison and as part of the DOE.

TRIAL 4: CROSSHEAD SPEED

- Pick a Trial 2 DOE for a fabric type.
- Add crosshead speed as an additional three level factor to the DOE.
- Run specimens for the additional part of the DOE, this being the two additional speeds.
- Analyze the entire DOE for Peak Load of the Load-Displacement Curves.

TRIAL 5: MOUNTING PROCEDURE

- Pick a circular specimen of the style and type used in Trial 1.
- Run the specimen 20 times per ring diameter on all ring diameters appropriate for the style.
- Do not pre-fold the specimen as in Trials 1, 2, 3, 4; hold the fabric flat (putting your palm underneath the specimen) prior to pulling through the ring.
- Compare peak loads of the Load-Displacement Curves with those of Trial 1.

3.5 Statistical Analysis

3.5.1 Subjective Hand Evaluation

Due to the size of the sample set, the comparative “all fabrics at a time” method for subjective ranking was used in this research. A paired comparison method was deemed too unwieldy, and also the variation between fabrics was in some cases so slight that it was helpful to include a range of fabrics in each evaluation set.

In order to evaluate the data, a logistic regression approach was used. A mathematical modeling tool, logistic regression can be used to describe the relationship of several independent variables to a dichotomous, or divided, dependent variable (18). Ordinal logistic regression, a form of polytomous or nominal logistic regression will be used to fit the ordinal responses of the subjective evaluation respondents. Ordinal logistic regression is appropriate to use in instances when outcome response variables have more than two categories, and when these categories have a natural order (18). The type of ordinal logistic model used was the proportional odds or cumulative logit model.

The odds ratio in its simplest form is the ratio of the probability that some event will occur over the probability that the same event will not occur (*P* divided by 1-*P*) (18). The odds ratio formula in logistic regression includes the independent variable X. The logit, or log odds for an individual X, is found by taking the natural log of the odds ratio, and with that said, the exponential form of the logit is the odds ratio (18). This comes into play in the analysis.

ODDS RATIO $[P(X) \div 1 - P(X)]$

- Describes risk in model for individual X

LOGIT P(X) $\ln_e [P(X) \div 1 - P(X)]$

- Log odds for individual X
- $= \alpha + \Sigma\beta_i X_i$

For this research, a verbal explanation of the odds ratio for fabric style A2 is the odds that A2 will be chosen as better than the control fabric D1 Control (D1C) in terms of the response variable extension. If the odds ratio < 1, fabric A2 is less likely to be chosen as better versus D1C. If odds ratio = 1, the odds of being chosen are the same for both A2 and D1C. If the odds ratio > 1, A2 is more likely to be chosen as better versus D1C.

In this research, there were six outcome response variables used in the subjective evaluation (preference, comfort, compression, extension, bending, and surface). The number of levels or categories for these response variables depended on the number of fabrics within a sample grouping. These outcome response levels were ordinal (ranging from 1 to 10 for fabric A, with 1 being the best for a response variable such as comfort, and 10 being the worst).

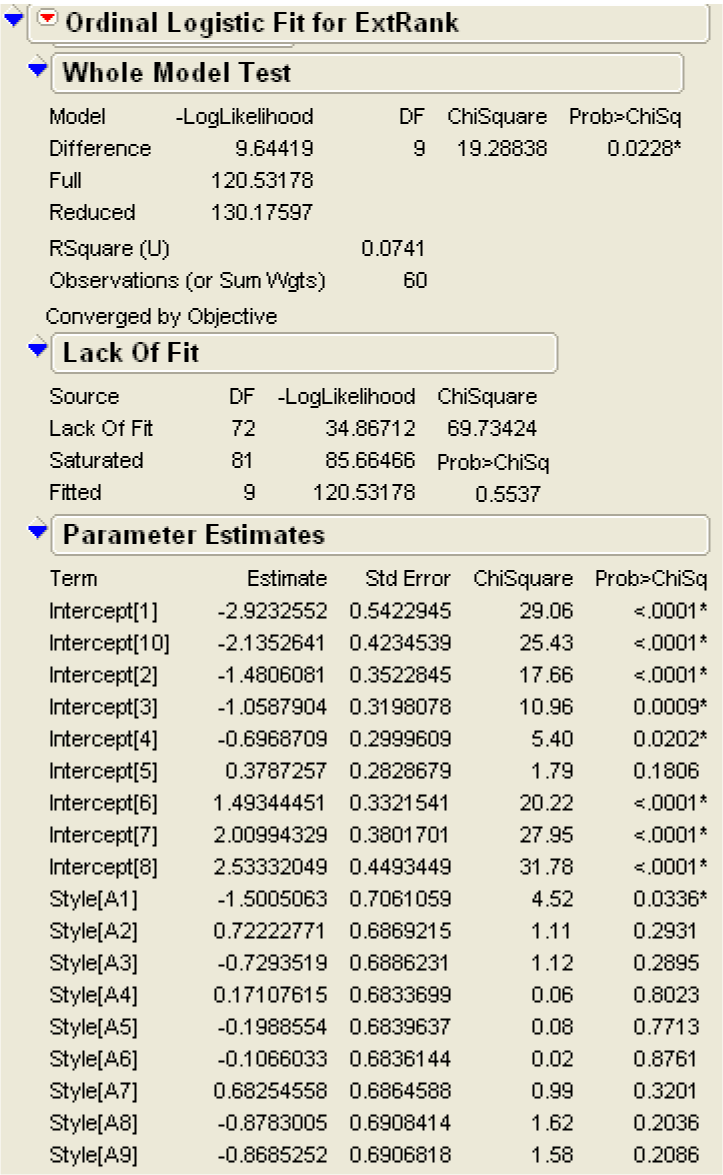
Fabric D1C was one of two controls included in every evaluation grouping during the subjective evaluation. In the logistic regression model, however, D1C was chosen as the basis for comparison over C3C because D1C was found to be more suitable across all fabric type groupings. After the data was collected, the polar fabric rankings (located on the extreme ends of the ranking scale) were thrown out, along with the rankings of the other constant, C3C.

The statistical software that was used was JMP 6.0.0 from SAS Institute Inc. In JMP, the ordinal data was arranged by subjective evaluation grouping, including only the styles within a fabric type and the constant (D1C). A Fit Model was run, specifying one of the six output response variables as Y. Fabric style was added as an effect. The model was run as Ordinal Logistic.

A likelihood-ratio Chi-square for the Whole Model Test was used to determine whether the difference in perceived response variables was significant. Chi-square p-values less than 0.06 were kept. The value 0.06 was chosen rather than 0.05 as a cut-off because there were a few that straddled the 0.05 line and this was a judgment call. With larger p-values, one can assume that the model is not adept at explaining the variation in respondents' ranking of fabric styles based on the response variable using only information about fabric type. This means that the model cannot explain the relationship between human preferences and fabric styles.

For fabric A, there were 9 degrees of freedom (DF) in the Whole Model Test. The output of this Ordinal Logistic Fit Model consists of two main sets of parameters, in this case nine intercept coefficients and nine fabric style coefficients (see

Figure 15). The proportional odds assumption rests on the idea that with ordinal data, there is a natural order to the output and the model is constrained. Therefore the odds ratio is the same for an independent variable regardless of how the levels of the output response variable are divided or grouped into segments. This means that only one coefficient is required for each of the independent variables for a given response variable. Therefore, there is a single coefficient for styles A1 through A9 when it comes to the response variable extension (ExtRank). There are also intercept coefficients that respond to each of the different levels of the response variable. Figure 15 is a JMP screen shot of the logistic regression model for extension ratings of fabric A:



```
Ordinal Logistic Fit for ExtRank
 Whole Model Test
 Model        -LogLikelihood      DF   ChiSquare   Prob>ChiSq
 Difference          9.64419       9    19.28838      0.0228*
 Full              120.53178
 Reduced           130.17597
 RSquare (U)                   0.0741
 Observations (or Sum Wgts)        60
 Converged by Objective
 Lack Of Fit
 Source            DF   -LogLikelihood   ChiSquare
 Lack Of Fit       72         34.86712    69.73424
 Saturated         81         85.66466   Prob>ChiSq
 Fitted             9        120.53178      0.5537
 Parameter Estimates
 Term               Estimate    Std Error   ChiSquare   Prob>ChiSq
 Intercept[1]     -2.9232552    0.5422945       29.06      <.0001*
 Intercept[10]    -2.1352641    0.4234539       25.43      <.0001*
 Intercept[2]     -1.4806081    0.3522845       17.66      <.0001*
 Intercept[3]     -1.0587904    0.3198078       10.96      0.0009*
 Intercept[4]     -0.6968709    0.2999609        5.40      0.0202*
 Intercept[5]      0.3787257    0.2828679        1.79      0.1806
 Intercept[6]     1.49344451    0.3321541       20.22      <.0001*
 Intercept[7]     2.00994329    0.3801701       27.95      <.0001*
 Intercept[8]     2.53332049    0.4493449       31.78      <.0001*
 Style[A1]        -1.5005063    0.7061059        4.52      0.0336*
 Style[A2]        0.72222771    0.6869215        1.11      0.2931
 Style[A3]        -0.7293519    0.6886231        1.12      0.2895
 Style[A4]        0.17107615    0.6833699        0.06      0.8023
 Style[A5]        -0.1988554    0.6839637        0.08      0.7713
 Style[A6]        -0.1066033    0.6836144        0.02      0.8761
 Style[A7]        0.68254558    0.6864588        0.99      0.3201
 Style[A8]        -0.8783005    0.6908414        1.62      0.2036
 Style[A9]        -0.8685252    0.6906818        1.58      0.2086
```

Figure 15: Subjective Analysis Fit Model-Fabric A Extension

The style coefficients consist of the logits for the styles within a fabric group. The exponential of these logits were then derived and the resulting odds ratios were recorded and used as the basis for comparison with FAST and Ring Pull-Through data.

Each of the six output response variables was run separately. All styles within type A, B, C, D, E, or F were given values for each response variable (preferred, comfort, compression, extension, bending, surface) based on the odds ratio of that fabric being chosen over the control for a particular response variable within its sample grouping. Outputs were saved for all response variables deemed significant by the Chi-square p-value of the Whole Model Test. This was performed for all fabric groupings (A, B, C, D, E, and F).

Aside from the Whole Model Test, the Lack of Fit Test in JMP was used to test the ordinal response model as compared to a nominal model. The nominal model is the polytomous model whereby there is no natural order to the categories of the outcome response variable. For instance, in a judging of eye color, nominal responses could be brown, green, blue, or hazel. With an ordinal model, you have a constraining of the variables due to the natural order (1, 2, 3, 4,…) and thus you have less degrees of freedom (DF). The model is expanded if the response is treated as normal because more coefficients are required for each independent variable (or fabric style). For Fabric A, the DF would be expanded to 72 with a nominal model. However, if the Prob>Chi-Square value is greater than 0.05, the nonsignificance of the Lack of Fit suggests that the ordinal model is reasonable as a basis of analysis (28). This was used as a gage during the analysis to make sure that the chosen model was appropriate. In all cases the ordinal response model was used.

3.5.2 FAST

Two graphical visual tools were chosen for the analysis of FAST output. The radar chart was chosen as a tool for analysis because these allow you to look at a number of variables all relating to one item, in this case 25 variables per style within a fabric type. The radar charts were created in Microsoft Office Excel 2003. In the charts created for the FAST data, there are 25 axes, each corresponding to a different FAST output variable, such as B-1, bending rigidity in the warp direction, found using FAST-2. The axes were ordered based on the FAST output ordering for the snake plot control chart. The order started with RS-1 and moved clockwise around the edge of the circle, ending with W, the weight measurement. It is acknowledged that a reordering of variables along these axes would affect the appearance of the chart.

In these charts, a point close to the center on any axis constitutes a low value within the sample group. A point near the edge constitutes a high value. The radar charts created were scaled so that the highest value for each test variable within the sample grouping was given a 1 rating.

The second tool that was used for analyzing FAST data was principal component analysis, a method of multivariate analysis. Principal component analysis was used as a quick visual tool for observing differences in fabrics based on values derived from FAST testing. Since the FAST output included values for 25 variables, it was important to find a way to express the data for a fabric type based on a reduced set of dimensions. As we saw in the radar plots, it is hard to visualize a space of 25 dimensions for a sample grouping of up to 9 fabrics.

Principal component analysis is a method for maximizing the variance of a linear combination of these 25 variables. The first principal component is defined as the direction of the linear combination of the variables that has maximum variance, subject to being scaled so that the sum of the coefficients is one (28). This consists of a dimension whereby the variables within a sample group are maximally spread out or separated from one another. The second principal component is the linear combination generated to have the maximum variance in the direction orthogonal (at a right angle) to that of the first principal component. Higher principal components are defined in the same way. There are as many principal components as there are variables (28). The principal components are extracted from the correlation matrix of all of the measured variables (26). In the case of FAST testing, this was 25 variables. It is the correlations in the data that form the principal components, and thus if the variables in the data are not correlated, all principal components generated will carry the same variance (28).

This method was mainly used as an exploratory tool, to give a general overview of the spread within a fabric type or grouping, and to identify potential outliers.

Principal components based on covariances were generated using JMP statistical software for a fabric type or grouping (fabric types E, F and C, D). When saved to the JMP data sheet, single values for each of the styles within a grouping were assigned for both principal component 1 and 2. These were then plotted, with values for principal component 1 on the x-axis and values for principal component 2 on the y-axis. Plots were generated to observe the tendency of points to cluster or group.

Decisions had to be made as to how many principal components to retain of the many that are generated by the software. The principal component report in JMP displays what portion of the variance among the variables is carried by each principal component. As a baseline, it was suggested to retain sufficient components to account for 80% of the total variance within a data set (26). For all groupings in this study, the total of the first two components was able to satisfy this requirement, pointing to there being a lot of redundant information in the FAST data. All 25 parameters were not needed to explain the data for each sample grouping, just two calculated parameters.

Scree plots of the eigenvalues of the principal components were also analyzed to ensure an appropriate number of selected components. The eigenvalues serve as variances of the principle components (26). An ideal pattern of a scree graph is shown in Figure 20. The first two eigenvalues form a steep curve followed by a bend and then a straight-line trend with a shallow slope. It is recommended that the components to be retained are those eigenvalues in the steep curve before the first point on the straight line (26). In the scree plot of Figure 16, two principal components were retained. This was in accordance with the cumulative percentage analysis, showing that 98.34% of the variance was explained by the first two principal components.

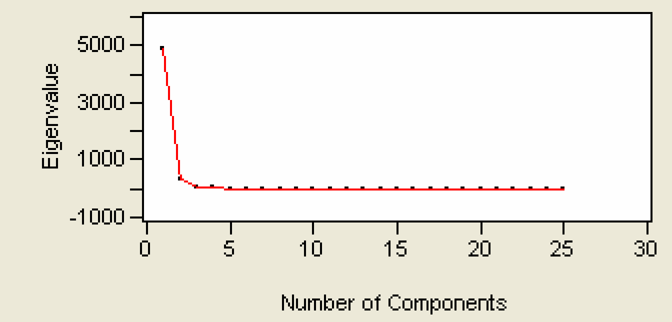


Figure 16: Scree Graph for FAST Principal Component Selection

Using bi-plots, the variation found within 25 dimensions is reduced to a two-dimensional view. When variables are close together on the bi-plot, it means that they represent most of the same information (28).

3.5.3 Ring Pull-Through

In the statistical analysis of the RPT data, area and peak load values for all fabric types were checked for normality using JMP 6.0.0. This began with an analysis of the shape of the distribution, and then proceeded with a Normal Quantile Plot, where it was noted whether the data stayed within the confidence limits and followed the predicted line. Finally, a Goodness-of-Fit Test was performed to derive a Shapiro-Wilk Test p-value for the normality assumption. The null hypothesis was that the data was normal. P-values < 0.05 suggested non-normality; with p-values greater than 0.05, we failed to reject the normality assumption (3). Table 5 shows the direction of statistical analysis taken for analysis of group means based on the results of normality:

Table 5: Statistical Analysis

Normality	Variance Statistic	Variance	P-value Used
Y	Bartlett's	Fail to reject	ANOVA
Y	Bartlett's	Reject	Welch's ANOVA
N	Levene's	Fail to reject / Reject	Nonparametric-Wilcoxon

If the data was not normal, the table shows that nonparametric methods were used to compare the means of the sample groups. These provide ways to analyze the test data that do not depend on assumptions about the distribution of the data (28). A Chi value of less than 0.05 would indicate that a statistical difference exists between group means.

3.5.4 Test Method Comparison

Multiple regression models are probabilistic models that include more than one independent variable. The following is the general form of the multiple regression model (22):

MULTIPLE REGRESSION MODEL $y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots. + \beta_k x_k + \varepsilon$

Where:

- y is the dependent variable
- $x_1, x_2, \ldots\ldots\ldots x_k$ are the independent variables
- β_0 represents the y-intercept of the line
- ε is the random error to make model probabilistic rather than deterministic
- β_i parameters determine the contribution of the independent variable x_i

The following methodology was used to conduct the multiple regression analysis (22):

- The deterministic data was collected, with values for $y, x_1, x_2, \ldots, x_k$.
- The deterministic part of the model was hypothesized, E(*y*), and independent variables were chosen for inclusion in the model (using JMP).
- Using JMP stepwise regression, regressors were narrowed down to no more than 3 per model.
- Variables were analyzed for collinearity using the multivariate scatterplot matrix for that style type.
- The method of least squares was used to estimate the unknown parameters $\beta_0, \beta_1, \ldots \beta_k$.
- Statistical evaluation of the model utility.
- Additional check for more significant models per dependent variable.

Due to the large amount of FAST variables, 25 in total, stepwise regression was used to experiment with different combinations of regressors. Mixed was chosen as the stepwise direction. After significant regressor variables were chosen, a model was run using only these regressors, this time using the least squares method. The method of least squares is based on choosing parameters such that their values minimize the sum of squared residuals. These parameters are the coefficients for the linear combination that defines the regression model (28). The least squares model then produced a y-intercept value, coefficients for the chosen regressors, and a p-value for the significance of the model.

When there is a close linear relationship between regressors, collinearity is an issue (22). For the FAST data, there is a large potential for collinearity with some of the test variables, namely the derived values for formability (F-1 and F-2), bending rigidity (B-1 and B-2), shear rigidity (G). To test for collinearity, scatterplot matrices of the FAST data were created using multivariate analysis. These were used to help identify variables for inclusion and exclusion in the pool of potential regressors. If the chosen variables appeared to be highly correlated with other variables in the matrix, they were locked out and the stepwise regression was re-run without those variables. At most three models of 3 regressors each were kept for each dependent variable analysis. Only statistically significant (p-value < 0.05) regression models were included in the table.

CHAPTER IV

4 Results

4.1 Subjective Hand Evaluation

Subjective evaluation rank order data is shown in Tables 24 through 29 in Appendix A. The following charts plot the odds ratios for the styles of each fabric type based on the subjective variable comfort. High values represent that a style was found to be more comfortable to judges, whereas low values indicate that the style was less comfortable.

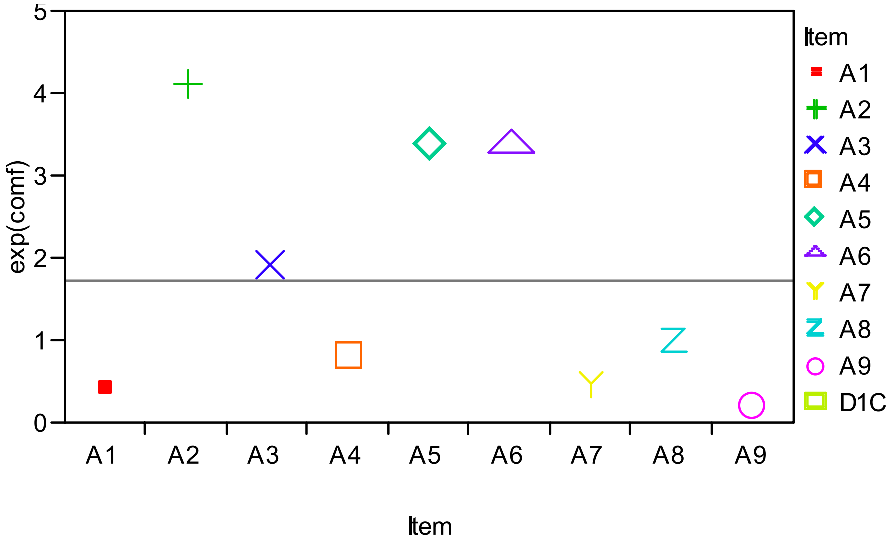


Figure 17: Fabric A Odds Ratio Plot

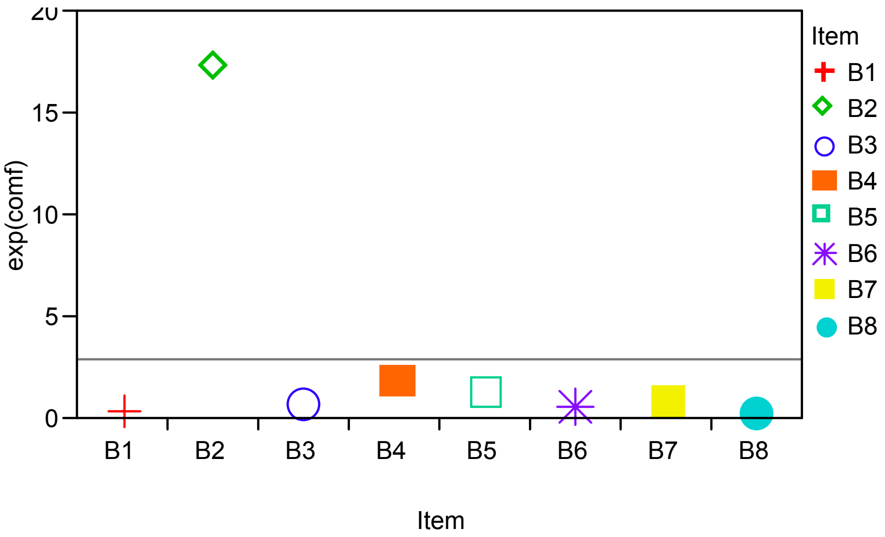


Figure 18: Fabric B Odds Ratio Plot

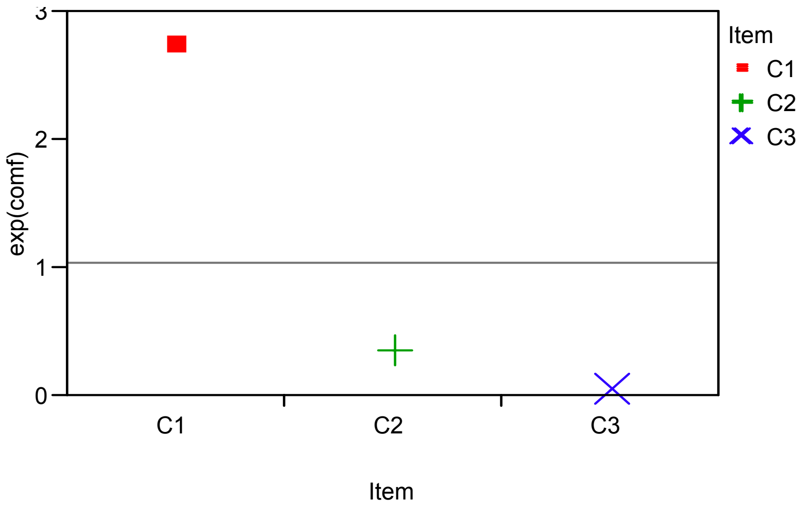


Figure 19: Fabric C Odds Ratio Plot

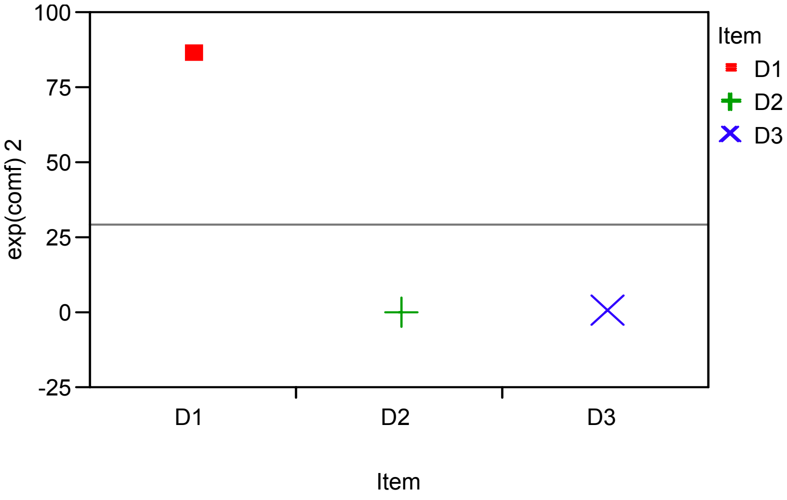


Figure 20: Fabric D Odds Ratio Plot

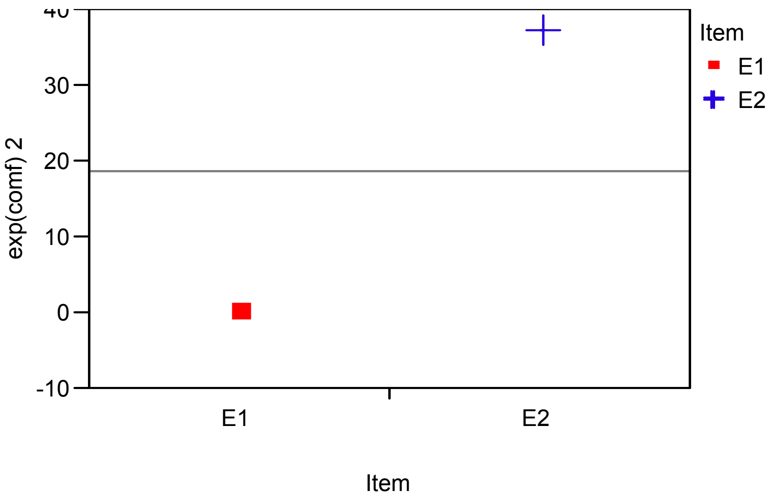


Figure 21: Fabric E Odds Ratio Plot

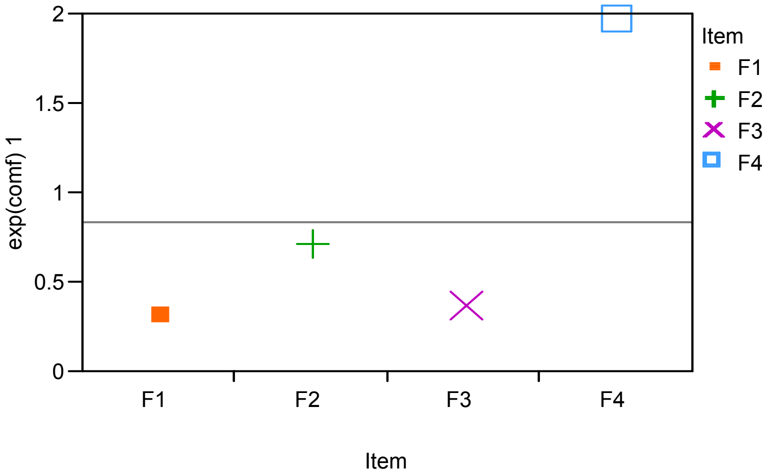


Figure 22: Fabric F Odds Ratio Plot

The plots for fabrics A and B show that fabrics A9 and B8, the easy-care finished fabrics, have the lowest means for subjective comfort. This means that the odds of these fabric styles being chosen as more comfortable than the control are the lowest within their respective fabric types. Apparently stretch or extension is very important to comfort as A2 and B2 (warp stretch-finished fabrics) had the highest means for both groupings. Therefore, the odds of these styles being chosen as more comfortable than the control are the highest within their types. In terms of fabrics C and D, respondents felt that the dyed versions would be more comfortable than the printed and DWR versions, however, in both cases, they had a hard time differentiating between the printed and DWR-finished styles. There was no confusion when it came to fabric E, as respondents universally picked the finished fabric over the greige. For fabric F, the denim, F4 was found to be the most comfortable.

4.2 FAST

FAST output consists of 25 variables. Table 6 shows the mean FAST values for all styles of fabric type A. Tables for all six fabric types are shown in Appendix A.

Table 6: Fabric A FAST Mean Results

TEST	UNITS	Fabric A								
Dimension Stability		**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**
RS-1	(%)	1.4	1.0	2.1	1.9	1.8	2.4	1.1	1.8	1.0
RS-2	(%)	0.2	-0.1	0.3	0.2	-0.2	0.3	0.6	0.5	0.3
HE-1	(%)	3.4	4.9	3.4	4.3	5.0	4.7	3.6	4.3	2.7
HE-2	(%)	4.8	4.6	5.9	4.7	5.0	5.0	4.7	4.9	4.1
Extension										
E5-1	(%)	0.9	0.8	0.4	1.4	0.7	1.0	0.5	0.9	0.7
E5-2	(%)	1.2	1.0	1.4	1.0	1.0	0.9	0.8	1.5	1.0
E20-1	(%)	1.6	2.1	0.9	2.5	1.8	2.0	1.1	1.7	1.5
E20-2	(%)	3.2	2.8	3.6	2.7	2.8	2.5	2.6	3.5	2.5
E100-1	(%)	2.9	5.2	2.3	5.1	4.6	4.6	2.8	3.8	3.7
E100-2	(%)	7.9	7.3	9.4	7.5	7.6	7.3	7.4	8.4	6.9
EB5	(%)	5.4	6.1	5.5	4.9	5.6	5.5	5.8	5.1	4.5
Bending										
C-1	(mm)	30.2	18.6	24.6	21.3	29.2	38.2	44.8	36.4	35.8
C-2	(mm)	9.8	25.4	22.1	21.3	19.0	29.7	37.8	26.7	41.6
B-1	(μN.m)	47.5	11.6	25.8	16.7	44.5	96.4	154.3	81.8	82.1
B-2	(μN.m)	1.6	29.2	18.7	16.8	12.3	45.3	92.7	32.4	128.4
Shear										
G	(N/m)	23.0	20.0	22.0	25.0	22.0	23.0	21.0	24.0	28.0
Formability										
F-1	(mm^2)	2.3	1.0	0.9	1.3	3.3	6.6	6.3	4.5	4.3
F-2	(mm^2)	0.2	3.5	2.7	2.0	1.5	5.0	11.4	4.3	13.1
Compression										
T2	(mm)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
T100	(mm)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
ST	(mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T2R	(mm)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
T100R	(mm)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
STR	(mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
W	(g/m^2)	175.0	182.0	177.0	177.0	182.0	177.0	175.0	172.0	182.0

4.2.1 Radar Plots

Figure 23 is a radar plot for fabric A. It appears that the greatest variation in fabric values for a test variable is within RS-2, relaxation shrinkage in the weft direction. The values, however, varied between -0.2% and 0.6%, therefore the spread was actually quite minimal. Other areas of variation appear to be F-1 and F-2, formability in warp and weft directions. Low values corresponded to a greater potential for seam pucker. The lowest value for F-2, and the only formability rating that fell in the range of seam puckering according to the FAST control chart was A1, the control. The highest value overall for formability (not likely to pucker) came from A9, the easy care finish. Bending rigidity in warp and weft directions, B-1 and B-2, was also a source of variation. The highest bending value overall came in the warp direction, B-1, from A7, the water/oil repellent treated fabric. The lowest bending in the warp direction came from A2, the chemically treated warp stretch fabric. In terms of B-2, A1, the control, had extremely low bending rigidity in the weft direction. The highest B-2 values came from A9, the washable easy care finished style. One can see that A9 claimed the highest values for a number of test variables, including F-2, C-2, B-2, G, T100R, and W. For many others A9 was near the outer edge.

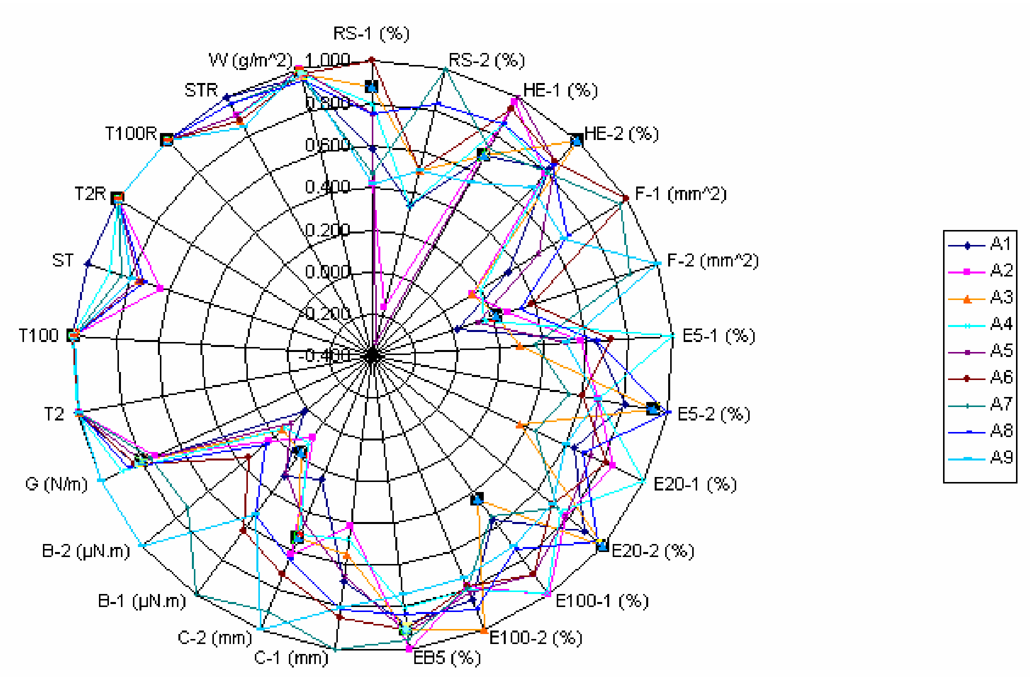


Figure 23: Radar Plot-Fabric A

The radar chart for Fabric B shows variations in RS-2, F-1, F-2, extension variables, B-1, and B-2. Again the only formability value that was in the range of seam puckering according to the FAST control chart was the control fabric, B1, for F-2. The warp stretch-treated fabric, B2, had the highest values for formability. B2 also had the highest values for extension in the warp direction under all loads (E5-1, E20-1, and E100-1). Bending values (C-1, C-2, B-1, B-2) were also high for this style in both warp and weft directions. The easy care finished fabric, B8, had the lowest extension values for nearly all parameters (second lowest in E100-1). Similar to fabric A, the easy care fabric came in highest for G, shear rigidity.

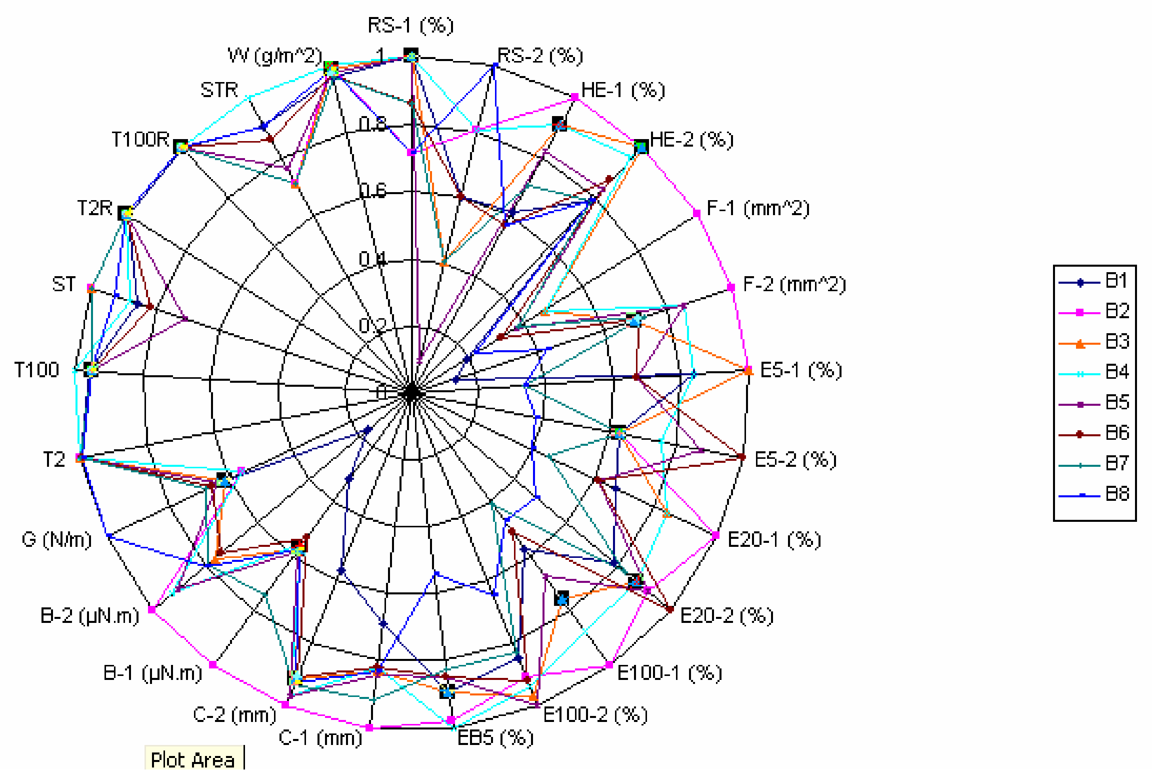


Figure 24: Radar Plot-Fabric B

For fabrics C and D, the differences between the 3 styles of each fabric type are easier to denote because of the reduced number in the grouping. Though different base fabrics, C and D underwent the same finishing treatments to arrive at the three styles within their fabric types. There are some similarities to be seen in the charts for both of these fabric types. For both C and D the printed versions (C2 and D2) displayed the highest shear rigidity, G. In both cases the DWR styles (C3 and D3) displayed the lowest formability values. There were some differences, however. Fabric D seemed to have more consistency than Fabric C. D1, the dyed style displayed the highest values for all extension variables. D2, the printed style, displayed the highest values for all bending variables (tying with D3 in some cases). Fabric C alternated in the category of extension values, with the printed fabric, C2, having higher extension in the warp direction at higher loads. The dyed fabric did have higher weft extension values however. The DWR style, C3, was consistently the highest in bending values. Fabric types C and D appear to have adhered to the hypothesis of Peirce, that dyeing reduces stiffness, while heavy printing increases stiffness (25).

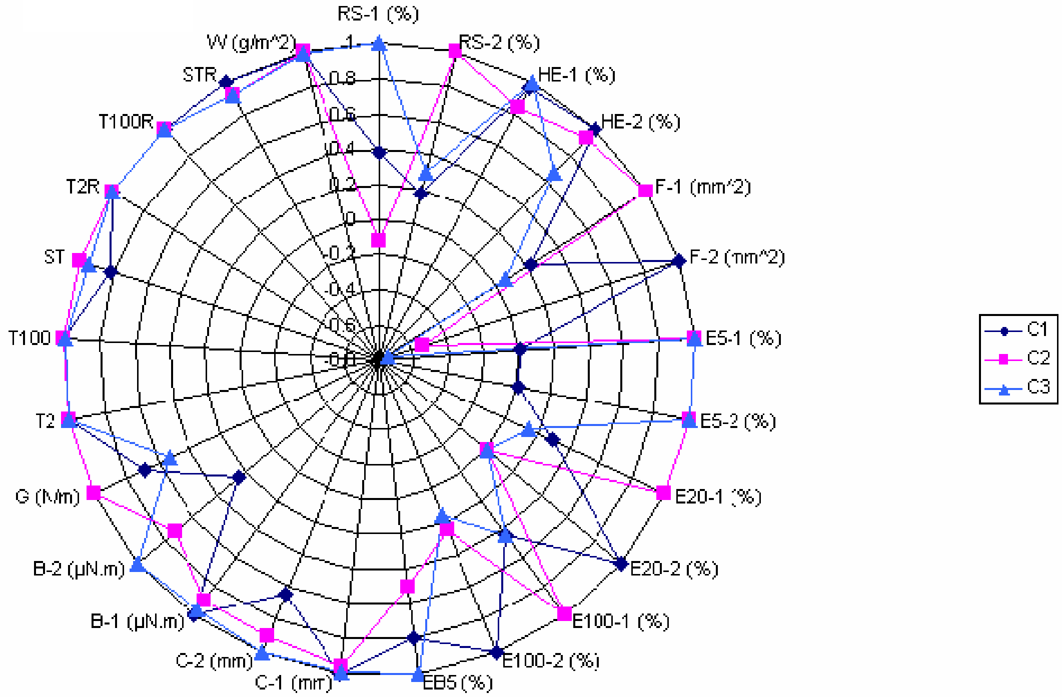


Figure 25: Radar Plot-Fabric C

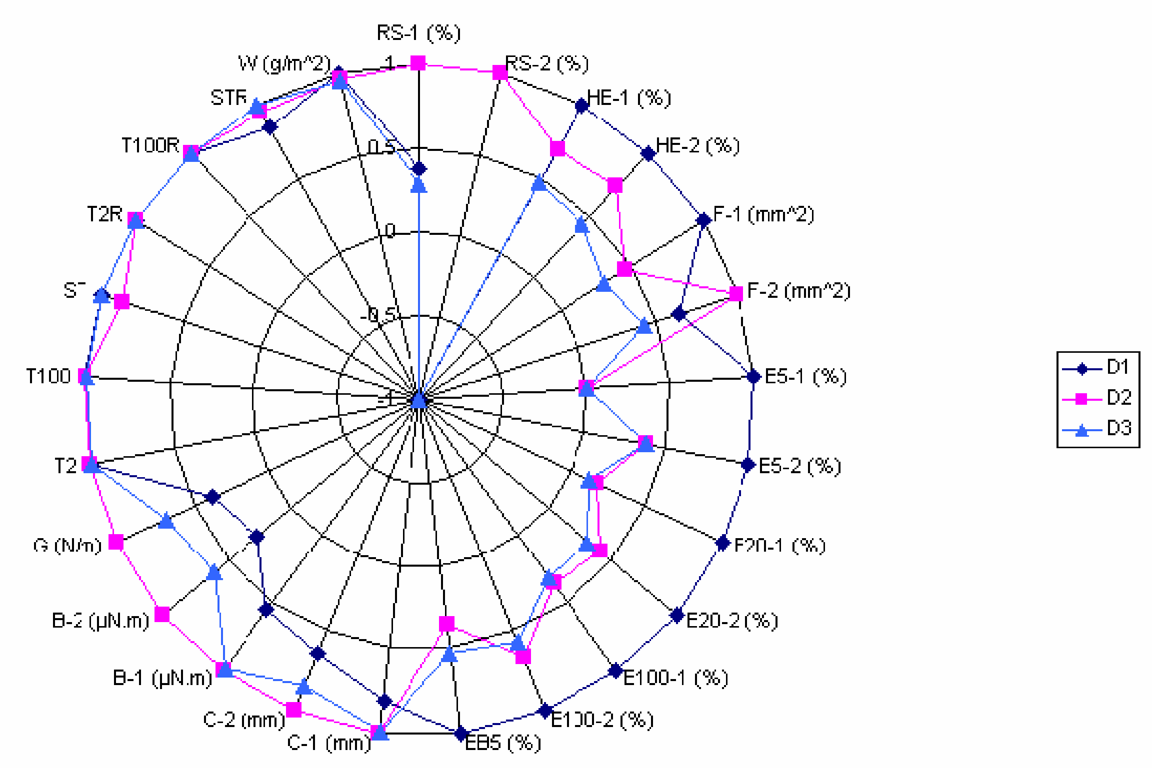


Figure 26: Radar Plot-Fabric D

Fabric E's results played out similarly to D, though with only two styles versus three. E1 had higher extension values and E2, the finished fabric had higher bending results. In terms of relaxation shrinkage and hygral expansion, the two styles flip flopped back and forth, based on warp and weft. Still all values were kept to below 1.2%, so the variation was not an issue.

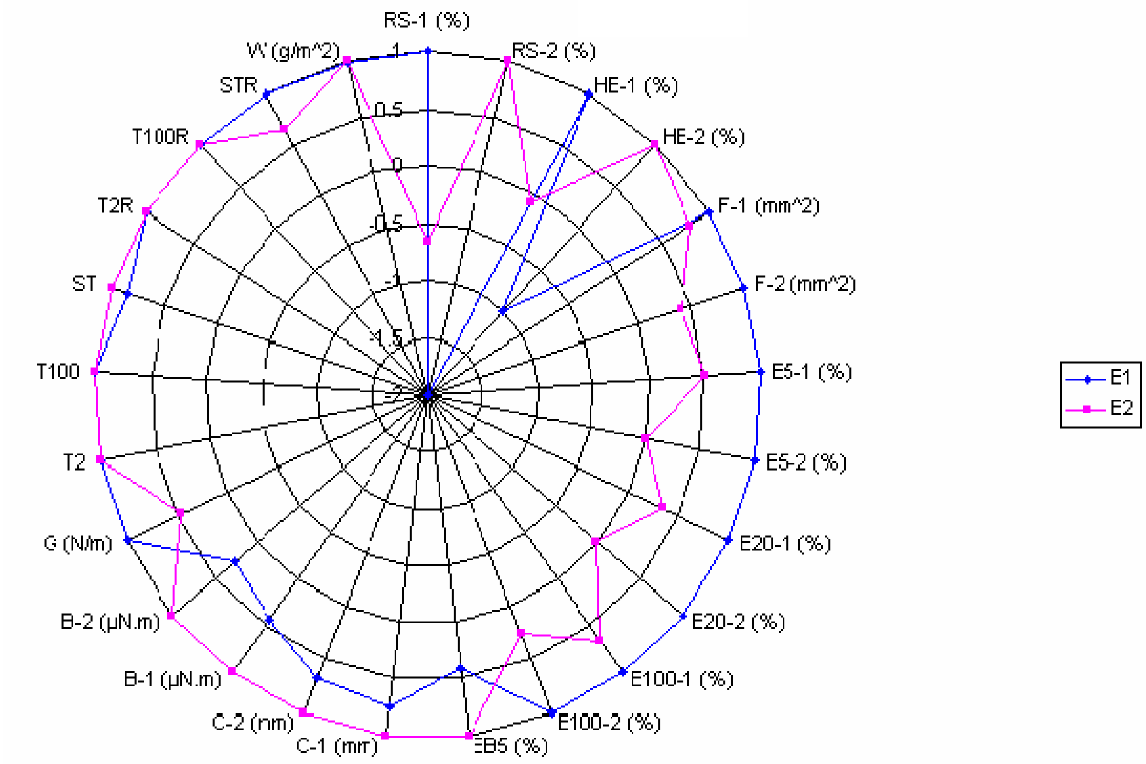


Figure 27: Radar Plot-Fabric E

Fabric F shows changes in roughly the same locations as the other fabric types. It is no surprise that F4 displays the greatest values in extension, as by this stage the fabric had undergone sanforization, a controlled compressive shrinkage process whereby the weight per meter and also stretch were increased. In terms of shear rigidity, G, as the stages of processing were performed, the fabric became less rigid. Extension could explain the preference of respondents for F4 in the subjective comfort plots. F3 was a stage of the finishing treatments whereby some of the highest numbers for rigidity were tabulated. The fabric was heat set on a tenter and evidently the heat treatment led to higher bending stiffness and poor formability values (though formability is partially derived from bending).

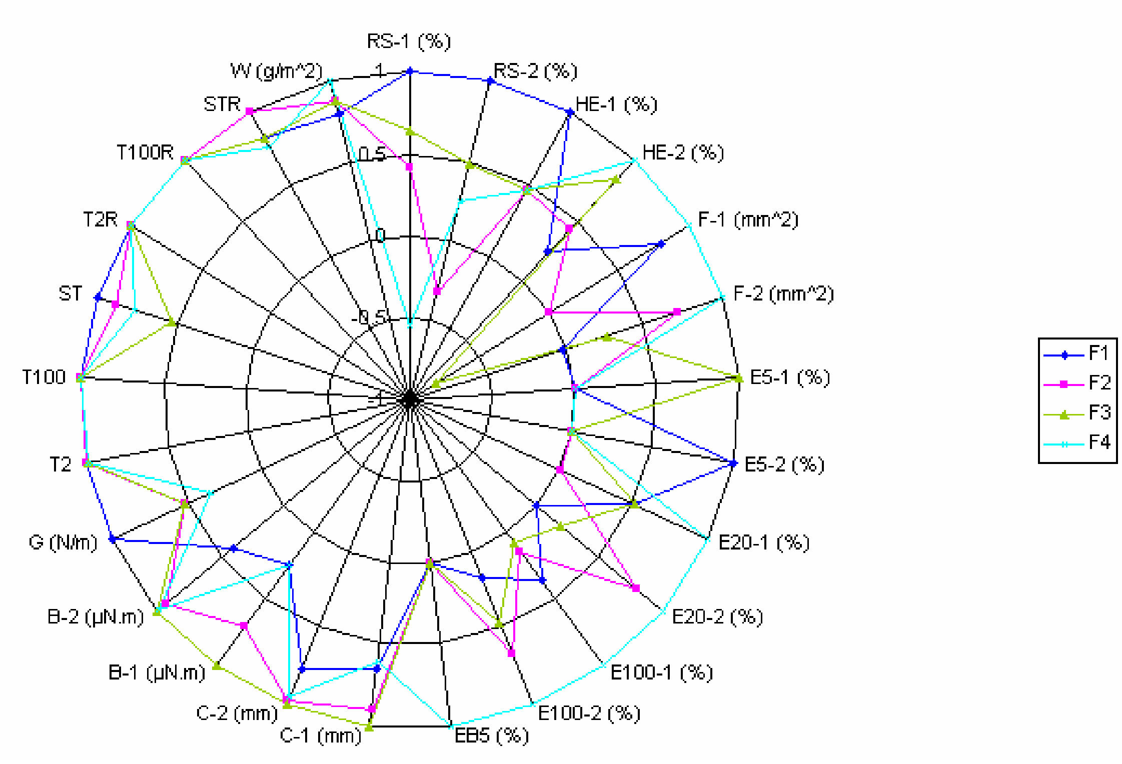


Figure 28: Radar Plot-Fabric F

4.2.2 Principal Component Analysis

Figure 29 is a bi-plot of principal components 1 and 2 for the styles of suiting fabric A. These first two principal components account for 99.75% of the variance found within the FAST results of this group. The bi-plot shows some clustering of styles to the left, with a few outliers to the right. With A1 as the control due to its lack of chemical finishing treatment, we see that the styles farthest away are A9 and A7. These two styles have functional finishes, with A9 having an easy care finish for washability and A7 with a water/oil repellent finish. Finished fabrics that share a common finishing treatment appear to be grouped together. A2 and A4 both were treated with a chemical to increase warp stretch, however, A4 also contained a softener. This was the same softening formula as used in A3. Additionally, A8 and A6 were both treated with softener 1, along with their other treatments. Perhaps it makes sense that A8 would lie on the same y-axis plane as A7, seeing as they both have a water/oil repellent finish. One might think that the positions of A6 and A8 would be switched as A8 has a water/oil repel and A6 shares a softener with A5, however, there appears to be an x-axis (principal component 1) reason for this ordering. When analyzing the eigenvectors of the first two principal components, Prin Comp 1 was dominated by variation in B-1 (bending rigidity in the warp direction) and Prin Comp 2 was dominated by variation in B-2 (bending rigidity in the weft direction).

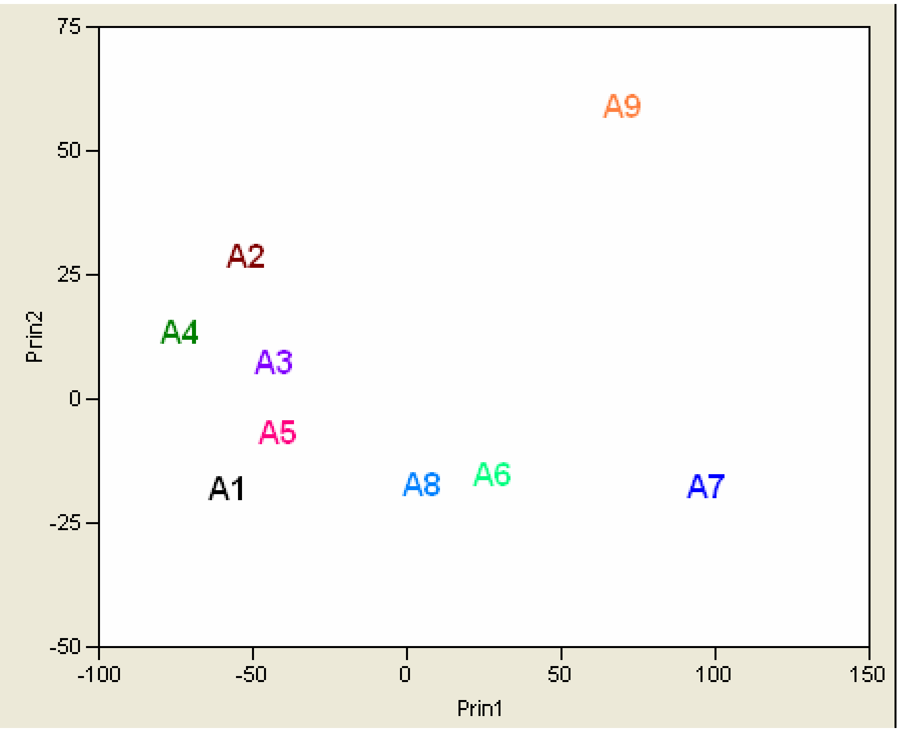


Figure 29: FAST Principal Component Analysis-Fabric A

In the bi-plot of the first two principal components of fabric B, we are again seeing clustering, with some noticeable outliers. These two principal components account for 89.6% of the variation found within the FAST results. This time the control, B1, is an outlier, again in the bottom left corner of the plot. Once again, the easy care washable finished fabric is on its own, farthest away from the control. Also, the warp stretch fabric, B2, is set off somewhat from the group, similarly to how it was in the subjective comfort plot. The main cluster in the center consists of all styles finished with a softening agent, and an unlikely B6, water/oil repel. Perhaps due to similar finishing treatments, we are seeing similar test variables dominating the eigenvectors of Prin Comp 1 and 2 of Fabrics A and B. Prin Comp 1 was equally dominated by B-1 and B-2. The greatest variation composing Prin Comp 2 was G, shear rigidity, a value calculated using bending length and bias extension from bias strips used in FAST-2 and 3.

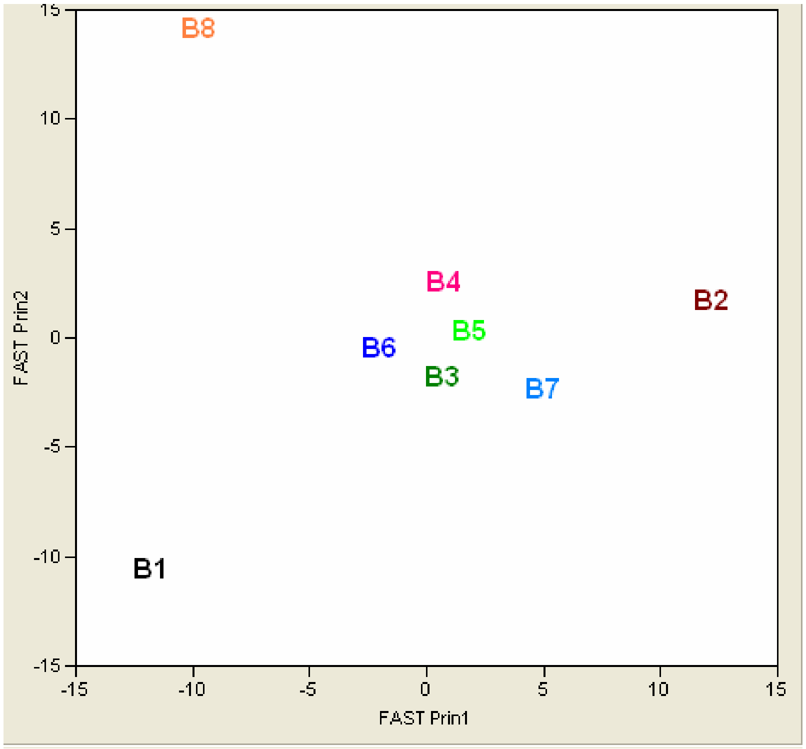


Figure 30: FAST Principal Component Analysis-Fabric B

Fabrics C and D were grouped together due to their similar finishing treatments. Summed, the first two principal components explained 98.34% of the variance. Looking at the bi-plot, we see that the styles of fabric D are clustered together more than those of fabric C. The only real takeaway from the plot other than that finding is that the least finished styles, in this case dyed-only samples D1 and C1, are oriented to the bottom left of the plot relative to the other styles within their groups. Variation in G, shear rigidity dominated the eigenvectors of Prin Comp 1. Prin Comp 2 was also influenced by changes in B-2, weft bending rigidity. Both of these variables, G and B-2 are derived from other FAST variables, as we will see later in the multivariate matrices.

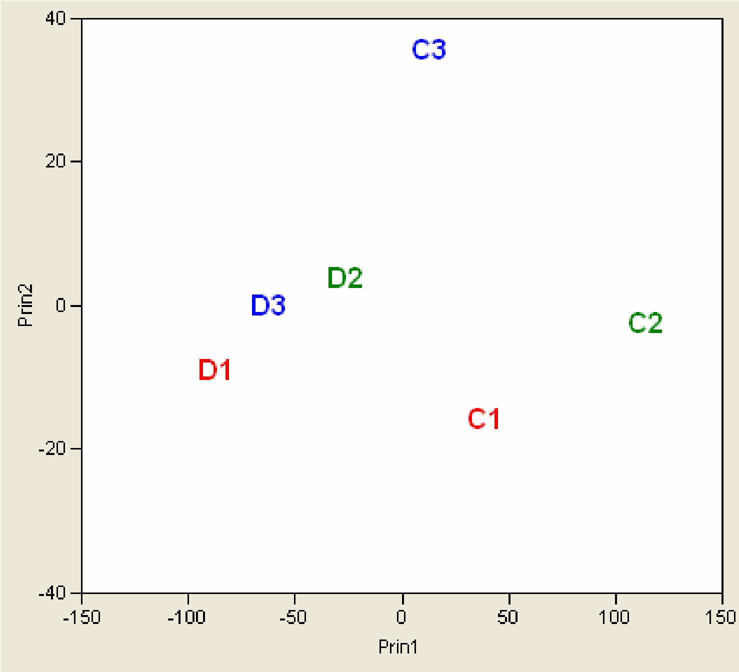


Figure 31: FAST Principal Component Analysis-Fabrics C, D

For fabrics E and F, the first two principal components account for 99.9% of the variation found within the FAST results. These styles were grouped together due to their higher weights and the fact that they had relatively few styles within their fabric groups. Again there is a greater clustering of one group over the other, this time fabric E. This may be due to the lower weight values of fabric E versus F. We are seeing a universal trend, however, of the least finished fabrics within a group (this time E1 and F1) being aligned in the low values of principal component 2 (the y-axis). It is not surprising that the style of F denim, F4, falls closest to the E napery styles, despite it having the highest weight within the grouping. The treatments of this denim fabric were made to largely improve the hand and wearing comfort of the denim, and F4 was the final stage of this process. We are seeing a trend as Prin Comp 1 is dominated by G, shear rigidity and Prin Comp 2 is largely based on B-1, warp bending rigidity.

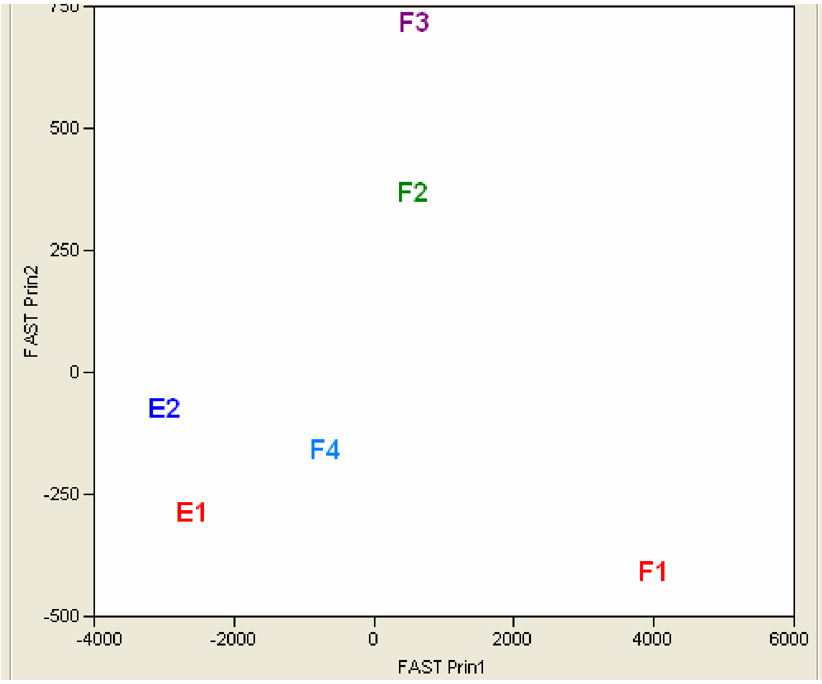


Figure 32: FAST Principal Component Analysis-Fabrics E, F

A grouping was created consisting of all six of the fabric types in this research. For all fabrics, the first two principal components account for 99.96% of the variation found within the FAST results. The markers are as follows: circles (fabric A), stars (B), squares (C), crosses (D), diamonds (E), and Z (F).

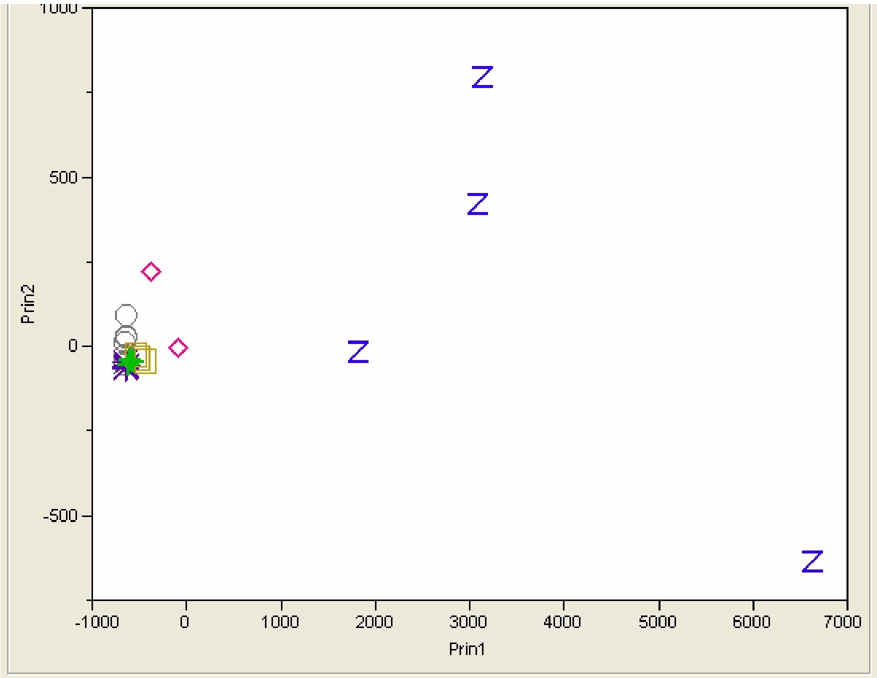


Figure 33: FAST Principal Component Analysis-All Fabric Types

One can see that there is extreme clustering of all fabric types in the plot but E and F. Fabric F is on its own, and E is closer to, but still cut off from the group. The "Z", or F style closest to the cluster is, no surprise, style F4, the style shown to have the highest comfort rating. The "Z" on its own to the right is F1. The original thought was that this clustering was due to weight, but weight was eliminated as a variable and the plot still remained the same. An analysis of the eigenvectors of the principal components showed that the greatest variation composing principal component 1 was G, shear rigidity. Principal component 2 was similarly dominated by one test variable, B-1, bending rigidity in the warp direction. The third component (not shown) was dominated by B-2, weft bending rigidity. This was not surprising as G, B-1 and B-2 all dominated the Prin Comp 1 and 2 landscapes for all fabric types.

4.3 Ring Pull-Through

4.3.1 Task 1

Task 1 consisted of one style of a fabric type being pulled through rings of multiple diameters. One circular specimen was used per fabric type. Task 1 was a repetition trial, to see if there appeared to be any trends associated with pulling a specimen through the ring for multiple runs. Task 1 also served as an initial gage of appropriate ring diameter for a fabric type. The styles used for this trial include styles A1, B1, C1, D1, E1 and F1. Some ring diameters were excluded for some styles due to the load cell range. Still, it was necessary to switch to a 250 N load cell for fabric types E and F for all trials, as these fabrics required more force than the 10 N would allow, despite the more limited diameter range.

Table 7: RPT Trial 1

		N Mean Peak Load (gm)					N Std Dev					n	N Range				
Type	Style	2 cm	2.5 cm	3 cm	4 cm	5 cm	2 cm	2.5 cm	3 cm	4 cm	5 cm		2 cm	2.5 cm	3 cm	4 cm	5 cm
A	A1	352.7	123.9	75.1	35.6	X	71.4	16.2	11.5	4.8	X	80	267.2	61.1	35.4	20.6	X
B	B1	311.5	125.3	79.1	35.2	X	59.4	18.9	9.5	4.7	X	80	207.7	76.1	42.1	18.3	X
C	C1	464.9	235.1	149.8	78.0	X	82.7	54.9	21.3	13.5	X	80	302.2	195.8	90.7	60.0	X
D	D1	273.8	96.2	52.6	18.0	X	37.6	13.2	7.6	5.2	X	80	160.5	45.8	30.0	17.2	X
E	E1	X	X	521.1	273.3	197.9	X	X	64.5	42.7	22.0	60	X	X	276.8	209.1	80.4
F	F1	X	X	X	816.7	531.4	X	X	X	103.4	68.6	40	X	X	X	382.7	234.7

The following are plots for all fabric styles:

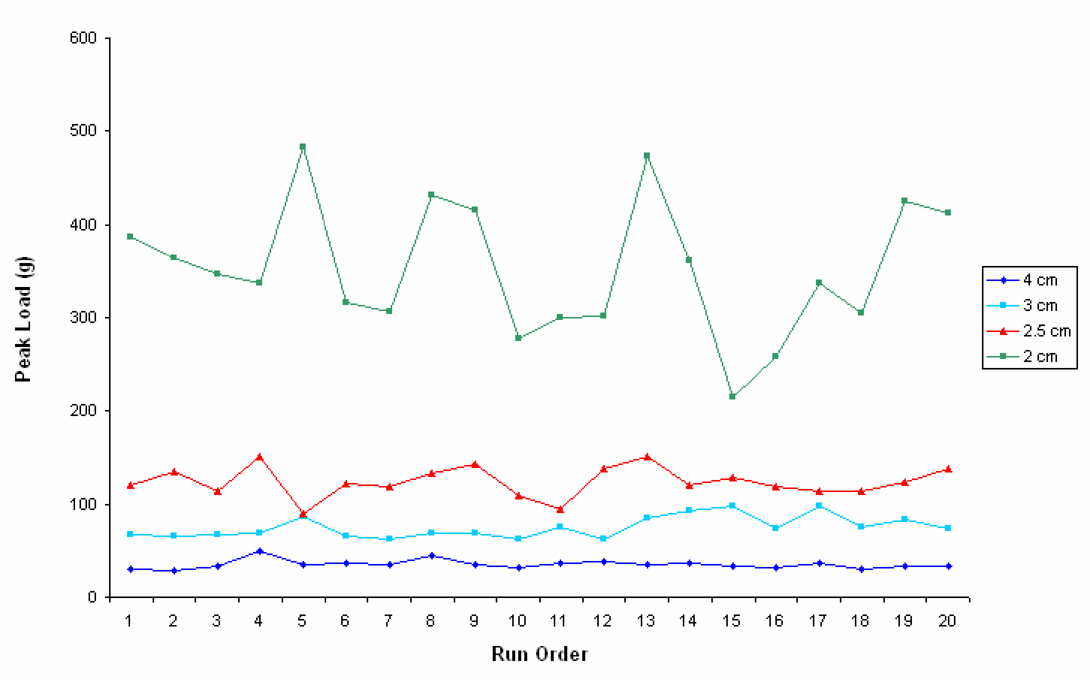


Figure 34: Fabric A Task # 1 Repetition Plot

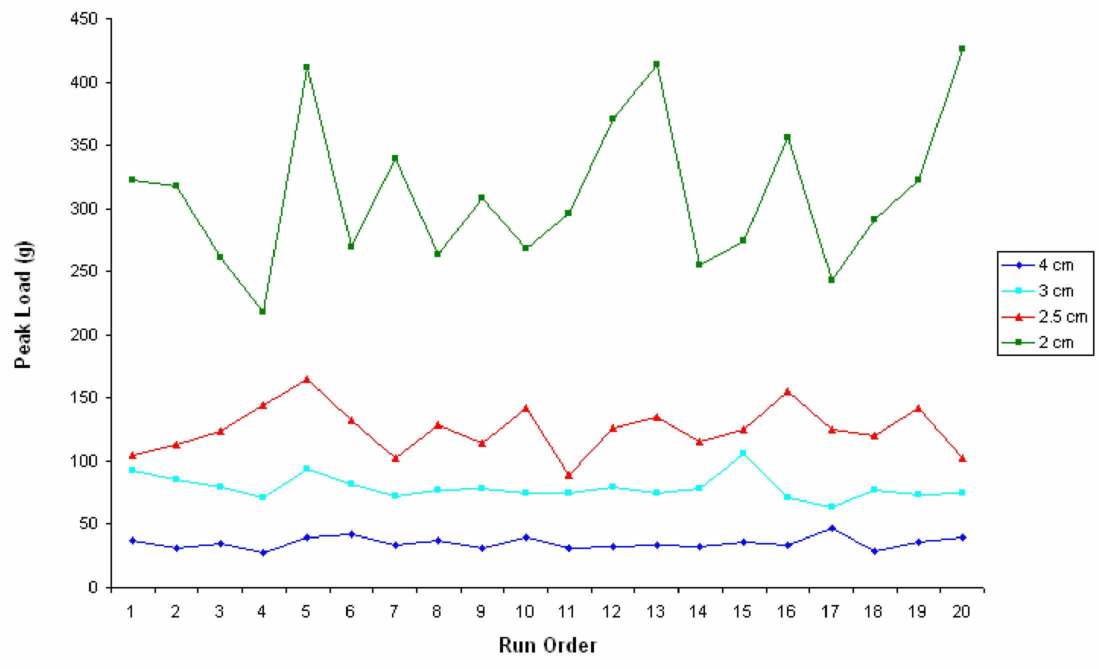


Figure 35: Fabric B Task # 1 Repetition Plot

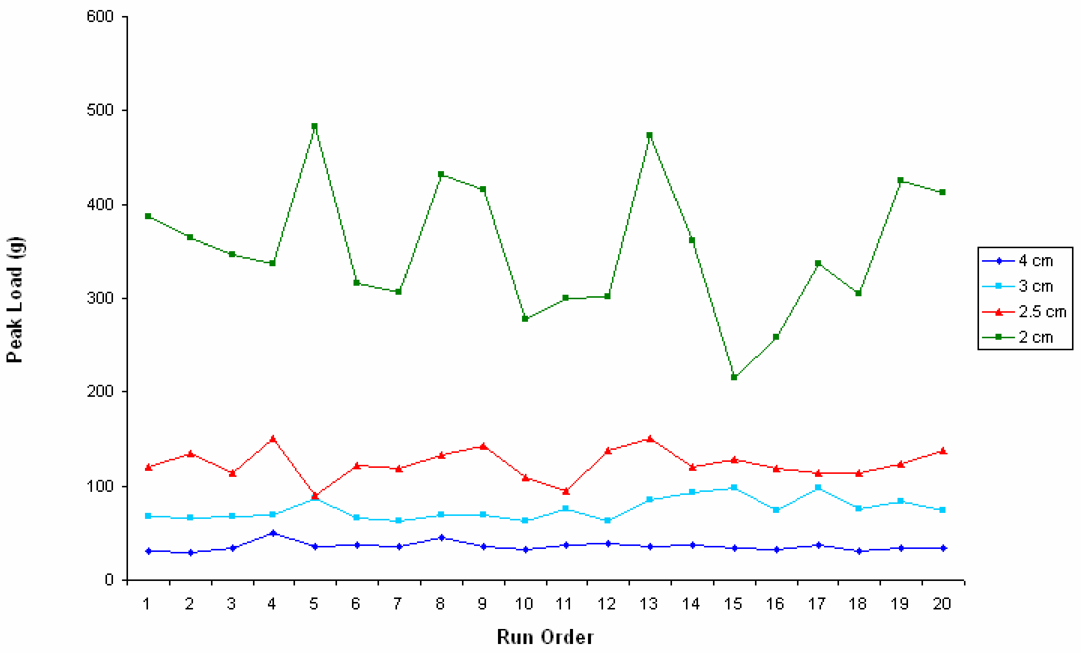


Figure 36: Fabric C Task # 1 Repetition Plot

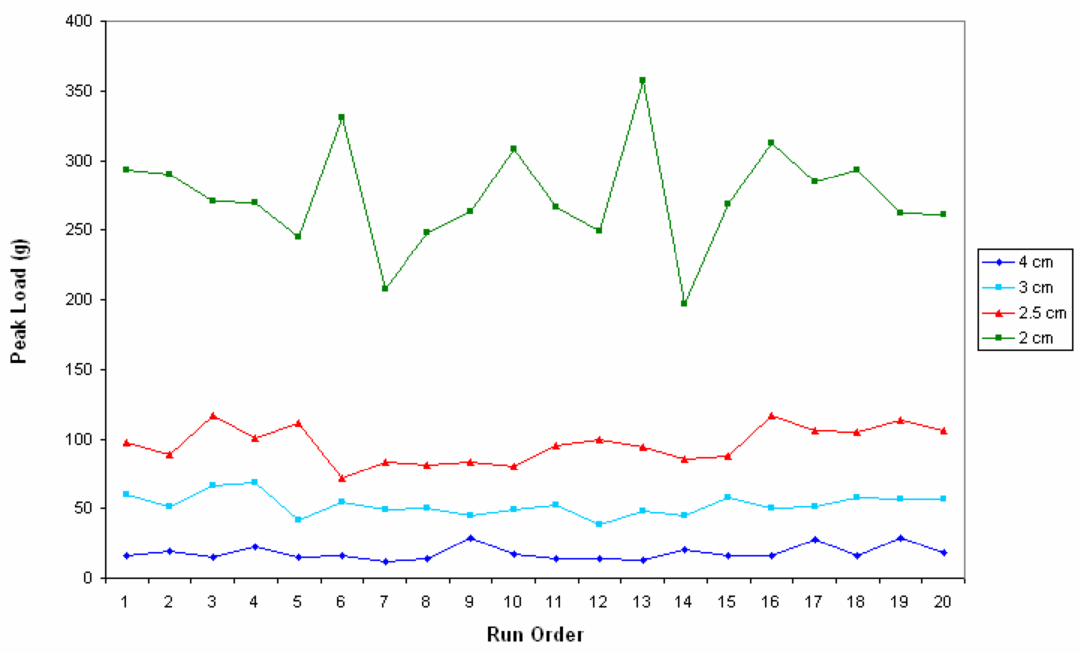


Figure 37: Fabric D Task # 1 Repetition Plot

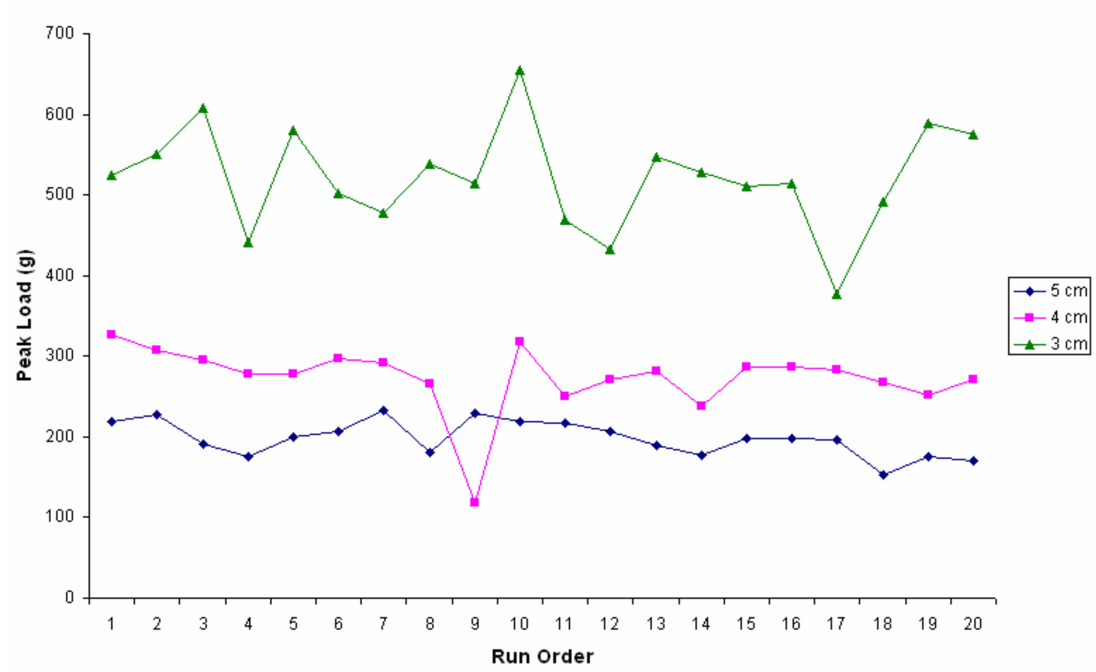


Figure 38: Fabric E Task # 1 Repetition Plot

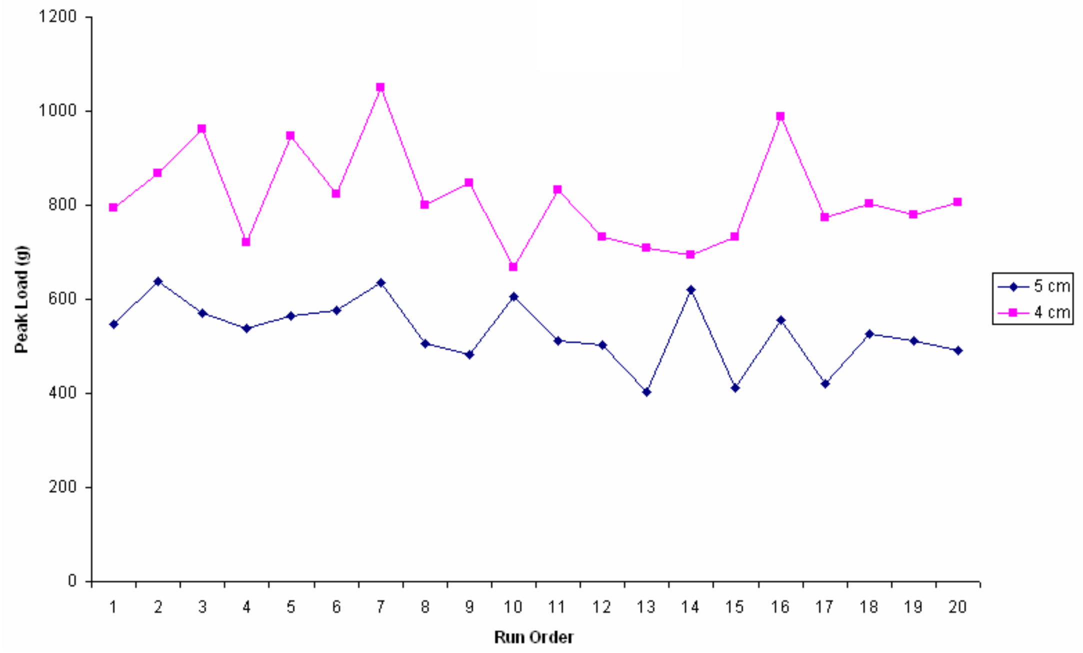


Figure 39: Fabric F Task # 1 Repetition Plot

The plots show that though there is a lot of variability discernible, especially in the peak loads of the smaller ring diameters, there does not appear to be any up or down trends experienced with repeated pulls, thus pointing to the idea that specimens can be used more than once in RPT trials. It can be seen for fabrics A, B, C, and D that the 2 cm ring diameter led to much higher peak loads and a wide range of values. This ring diameter resulted in sensitivity that was beyond the desired level. On the other hand, the 4 cm ring produces low peak load values, with a tight range leading to a flat line impression. This type of information was used in conjunction with the results from Task 2 to make the appropriate ring diameter and style assignments for Task 3.

4.3.2 Task 2

Task 2 consisted of two styles of a fabric type being pulled through rings or cylinders of multiple diameters. The purpose of Task 2 was to select the appropriate ring size to run further Design of Experiments for a particular fabric type. This trial served to screen out ring sizes that either produced too much variability or resulted in flat curves. Which diameter ring to use for each fabric type was, in a way, an educated guess. Efforts were made to choose a fabric type and ring diameter combination that was sensitive enough to be able to differentiate between styles within a fabric type.

Table 8: RPT Trial 2 Data for Normal Ring

			N Mean Peak Load (gm)					N Mean Area (gm*cm)				
Type	Style	n	2 cm	2.5 cm	3 cm	4 cm	5 cm	2 cm	2.5 cm	3 cm	4 cm	5 cm
A	A1	8	252.9	112.4	72.6	39.2	X	1640.6	655.3	467.9	255.4	X
A	A7	8	431.1	125.4	70.6	30.7	X	2313.2	632.4	414.4	154.6	X
B	B1	8	313.2	138.1	89.6	28.9	X	1975.7	758.5	493.6	150.6	X
B	B6	8	294.7	102.6	61.7	28.2	X	1726.0	655.0	350.6	133.2	X
C	C1	6	X	213.9	156.1	68.3	X	X	1363.9	848.8	308.7	X
C	C2	6	X	418.2	274.9	141.4	X	X	2833.9	1650.9	774.4	X
C	C3	6	X	503.5	522.4	200.7	X	X	3106.0	3050.9	1031.7	X
D	D1	6	X	98.9	67.9	19.4	X	X	477.9	291.9	113.7	X
D	D2	6	X	155.3	86.0	54.9	X	X	980.1	453.3	267.6	X
D	D3	6	X	187.5	167.7	62.1	X	X	1364.3	1050.1	382.5	X
E	E1	15	X	X	564.0	259.9	197.1	X	X	3071.4	1249.0	748.1
E	E2	15	X	X	854.8	371.1	259.7	X	X	5125.8	1920.6	1098.4
F	F1	10	X	X	X	952.1	621.5	X	X	X	4663.0	2412.5
F	F4	10	X	X	X	815.4	598.2	X	X	X	4368.6	2213.7

Table 9: RPT Trial 2 Data for Cylinder

			C Mean Peak Load (gm)					C Mean Area (gm*cm)				
Type	Style	n	2 cm	2.5 cm	3 cm	4 cm	5 cm	2 cm	2.5 cm	3 cm	4 cm	5 cm
A	A1	8	348.8	147.6	86.2	41.3	X	3120.2	1108.0	618.4	328.3	X
A	A7	8	436.2	126.5	72.7	40.5	X	3442.8	1029.0	1017.6	311.4	X
B	B1	8	329.6	120.9	91.3	44.0	X	2542.5	886.3	686.9	285.1	X
B	B6	8	405.1	96.8	86.9	34.1	X	3211.6	784.3	605.0	265.3	X
C	C1	6	X	241.3	164.0	76.5	X	X	1423.5	1099.6	416.9	X
C	C2	6	X	409.3	302.9	173.7	X	X	2995.0	2087.4	1018.0	X
C	C3	6	X	520.4	374.6	216.9	X	X	3526.5	2560.7	1087.8	X
D	D1	6	X	92.4	56.5	19.0	X	X	630.8	406.5	107.6	X
D	D2	6	X	178.9	166.3	41.6	X	X	1169.4	1149.4	281.5	X
D	D3	6	X	208.2	161.1	56.1	X	X	1801.2	1072.7	403.1	X
E	E1	15	X	X	621.1	332.8	182.9	X	X	4468.5	1969.0	975.1
E	E2	15	X	X	840.6	443.4	240.2	X	X	6083.0	2622.3	1172.4
F	F1	10	X	X	X	1004.6	616.4	X	X	X	6371.6	3155.8
F	F4	10	X	X	X	1047.4	571.9	X	X	X	7088.6	2868.7

Task 2 area and peak load data did not follow the normal distribution for all fabric types. There was not an adequate sample size for each condition of variables to warrant a true estimation of distribution normality, however.

Figure 40 shows a vertical bar chart of the standard deviation of the peak load and area for the load-displacement curves for fabric A. Ring diameters of 2 and 3 cm are shown to have larger standard deviations than 2.5 and 4 cm diameter rings. Additionally, the 2 cm rings are shown to give significantly higher values. The 4 cm diameter ring and cylinder provided flat curves, as the fabric easily slid through, with little compressional force being placed on the fabric. Based on the bar chart, the analysis of means from the Wilcoxon Test, and the visual representation of the Tukey-Kramer circular diagram, a ring and cylinder diameter of 2.5 was chosen for fabric A Task 3.

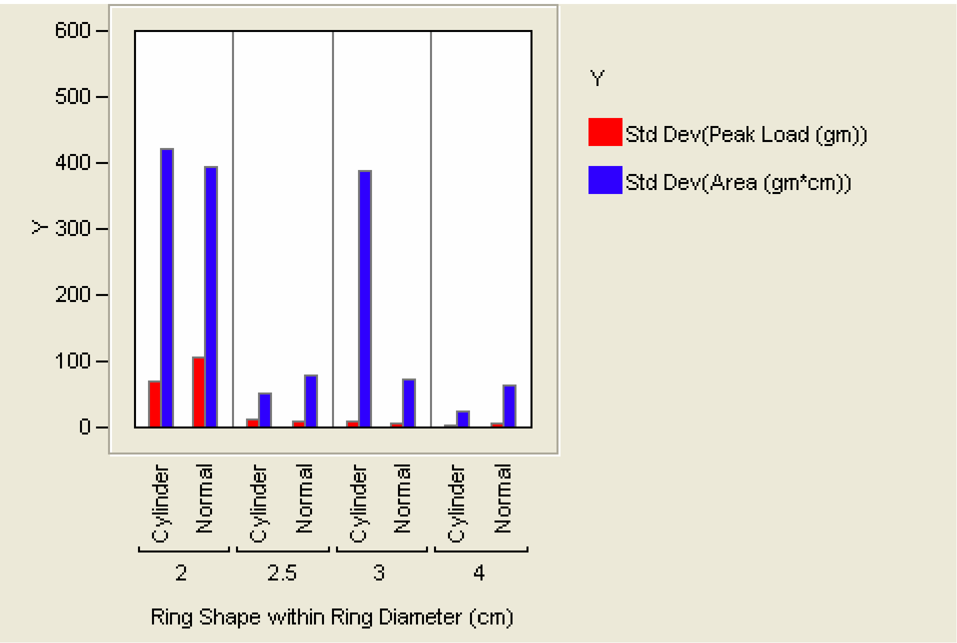
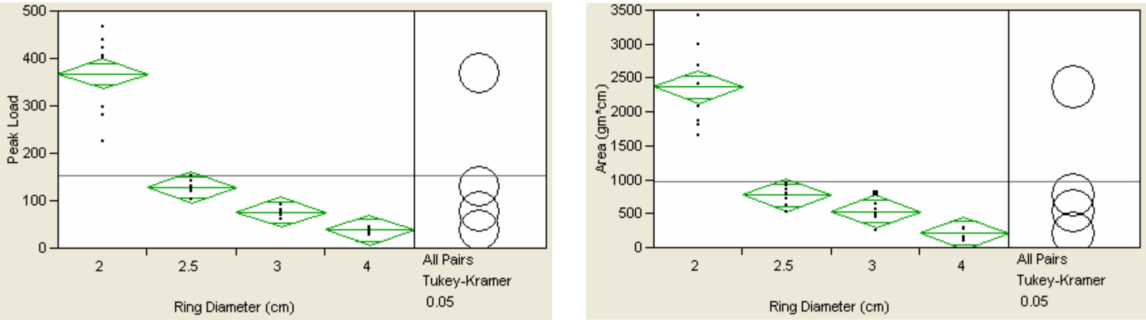


Figure 40: Fabric A Task 2 Standard Deviation by Diameter



Prob>ChiSquare = <.0001 Prob>ChiSquare = <.0001

Figure 41: Fabric A Task 2 Wilcoxon

Similar results were seen for fabric B. Ring diameter 2 cm was significantly different than the other three ring diameters in terms of peak load and area under the curve. This was displayed in terms of higher standard deviations as well. Ring diameter 2.5 cm was chosen as the appropriate ring diameter for Task 3 DOE for style comparisons. (See Figures 42, 43).

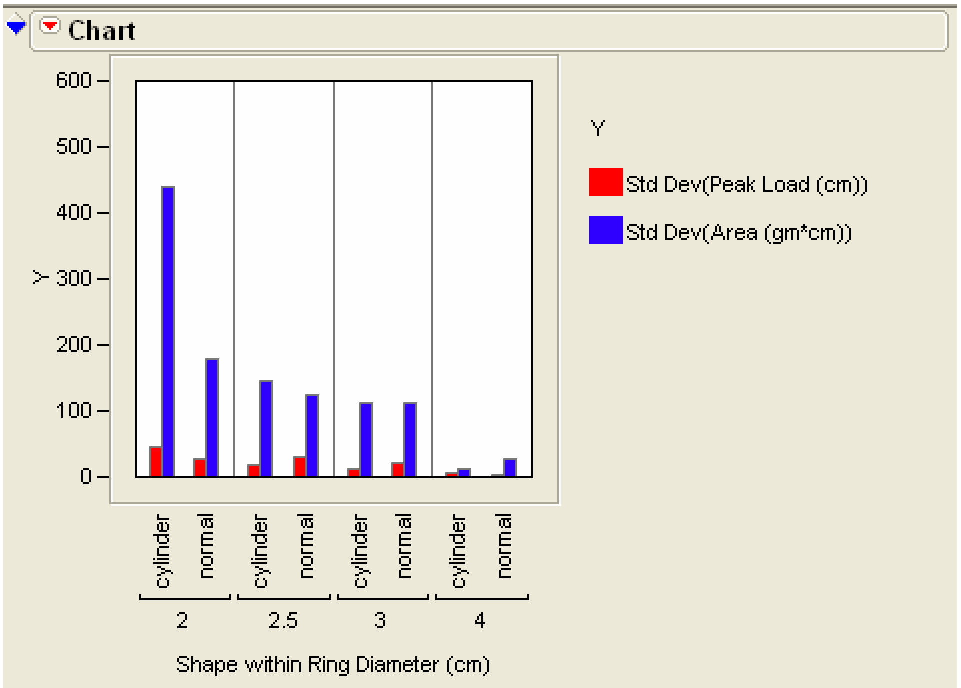
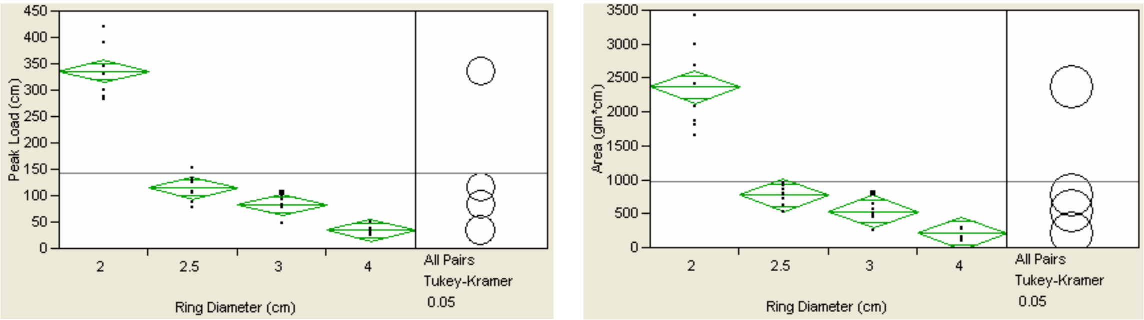


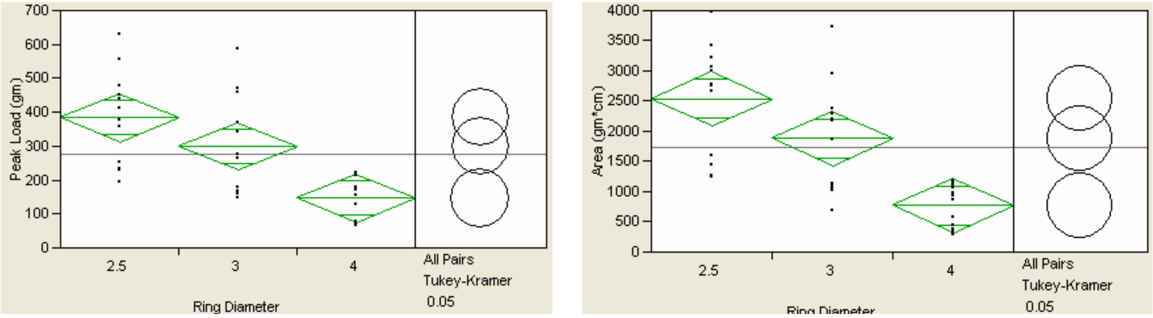
Figure 42: Fabric B Task 2 Standard Deviation by Diameter



Prob>ChiSquare = <.0001 Prob>ChiSquare = <.0001

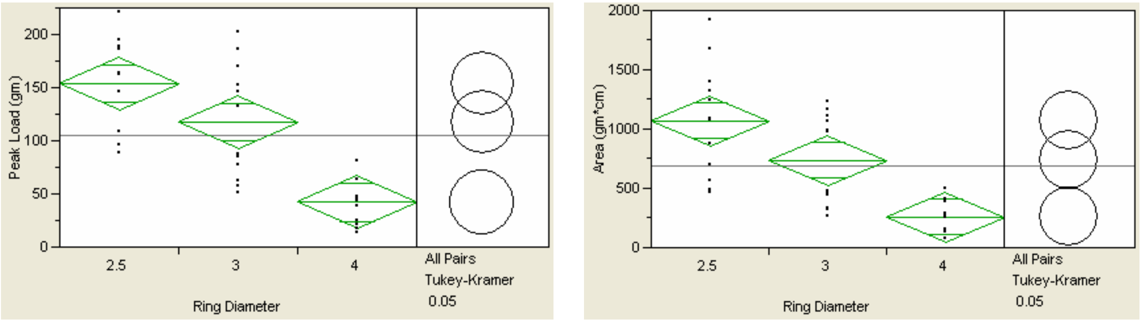
Figure 43: Fabric B Task 2 Wilcoxon

For fabrics C and D, the decision was between the 2.5 and 3 cm diameters due to the large statistically significant difference between these and the 4 cm diameter. The 2.5 cm diameter was chosen for both fabric types.



Prob>ChiSquare = <.0003 Prob>ChiSquare = <.0001

Figure 44: Fabric C Task 2 Wilcoxon



Prob>ChiSquare = <.0001 Prob>ChiSquare = <.0001

Figure 45: Fabric D Task 2 Wilcoxon

The 4 cm diameter was chosen for fabric E. The 5 cm diameter was an obvious choice for fabric F, as the 4 cm had standard deviations far too large to accurately assess the differences in fabric styles.

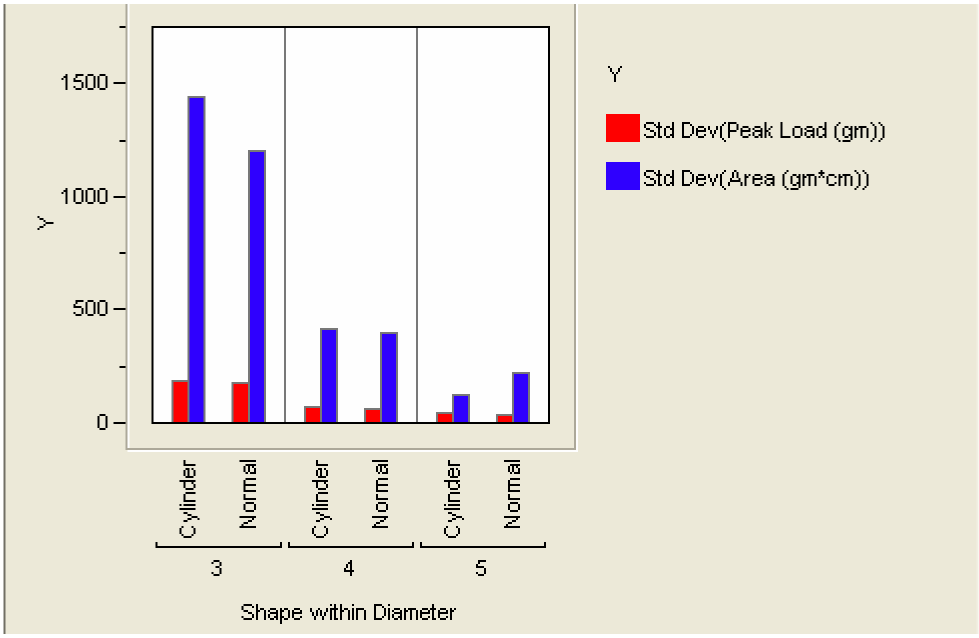
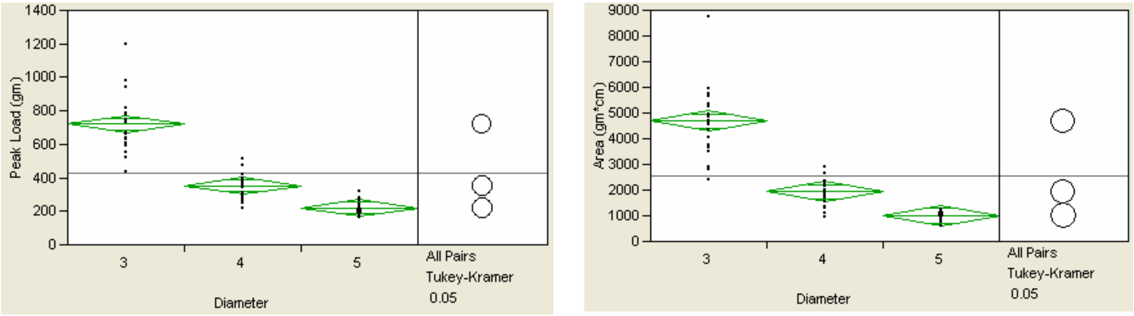


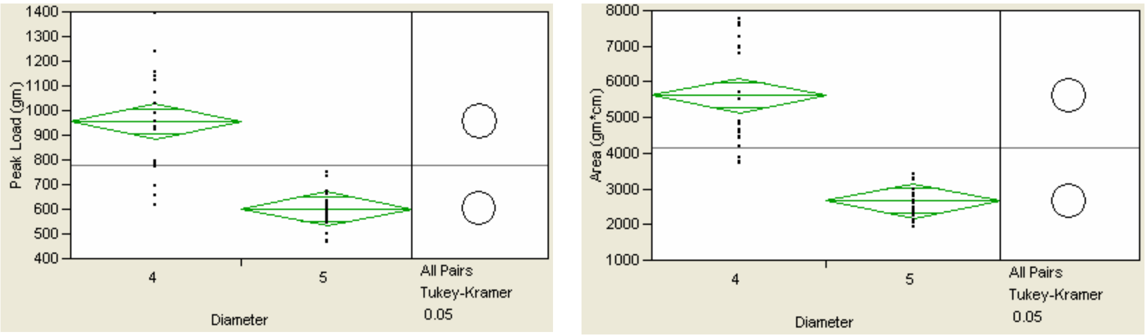
Figure 46: Fabric E Task 2 Standard Deviation by Diameter



Prob>ChiSquare = <.0001

Prob>ChiSquare = <.0001

Figure 47: Fabric E Task 2 Wilcoxon



Prob>ChiSquare = <.0001 Prob>ChiSquare = <.0001

Figure 48: Fabric F Task 2 Wilcoxon

4.3.3 Task 3

Task 3 consisted of all styles of a fabric type being pulled through a ring and cylinder of one predetermined diameter. This was repeated with four replications for all styles within a fabric type for both the ring and the cylinder.

Table 10: RPT Trial 3 Data for Normal Ring

		N Peak Load				N Area			
Type	Style	Mean	Std Dev	n	Range	Mean	Std Dev	n	Range
A	A1	121.3	16.7	5	38.0	779.9	147.5	5	367.6
A	A2	131.2	20.9	5	52.2	876.4	162.8	5	425.3
A	A3	105.0	19.1	5	53.3	627.5	99.1	5	205.3
A	A4	126.7	14.1	5	35.5	783.6	63.0	5	154.8
A	A5	126.9	32.5	5	82.0	795.0	165.8	5	435.8
A	A6	102.2	7.5	5	14.6	727.1	69.7	5	174.8
A	A7	126.3	21.0	5	57.5	782.9	138.6	5	338.5
A	A8	120.3	24.0	5	60.5	770.0	147.0	5	379.0
A	A9	163.5	20.5	5	53.3	1017.3	81.3	5	189.2
B	B1	101.9	12.4	5	29.4	675.8	103.2	5	261.5
B	B2	90.6	21.7	5	47.4	597.1	126.6	5	297.1
B	B3	82.9	9.5	5	21.4	583.1	47.4	5	97.5
B	B4	104.6	24.1	5	58.0	593.6	85.1	5	184.4
B	B5	82.7	11.4	5	28.2	500.7	39.6	5	101.0
B	B6	99.4	22.2	5	61.9	602.7	149.5	5	359.7
B	B7	144.6	41.2	5	109.0	799.9	170.0	5	437.0
B	B8	105.8	20.1	5	49.2	670.6	93.4	5	255.9
C	C1	274.9	70.4	5	186.1	1559.8	485.5	5	1226.9
C	C2	554.7	90.5	5	205.0	3102.2	354.9	5	863.6
C	C3	629.8	104.9	5	266.0	3821.7	710.4	5	1900.3
D	D1	104.6	23.4	5	63.6	587.0	98.1	5	227.0
D	D2	256.8	45.1	5	109.0	1459.6	213.0	5	513.6
D	D3	343.2	67.0	5	187.6	1723.2	292.9	5	712.1
E	E1	346.4	98.6	5	226.1	1899.5	605.6	5	1624.5
E	E2	427.7	48.1	5	122.5	2253.8	213.4	5	536.1
F	F1	597.3	46.1	5	128.0	2416.9	73.7	5	189.1
F	F2	950.2	154.9	5	408.1	3692.6	511.0	5	1376.6
F	F3	1203.2	297.3	5	697.1	4649.8	699.5	5	1693.3
F	F4	577.0	57.6	5	150.2	2758.6	363.3	5	883.5

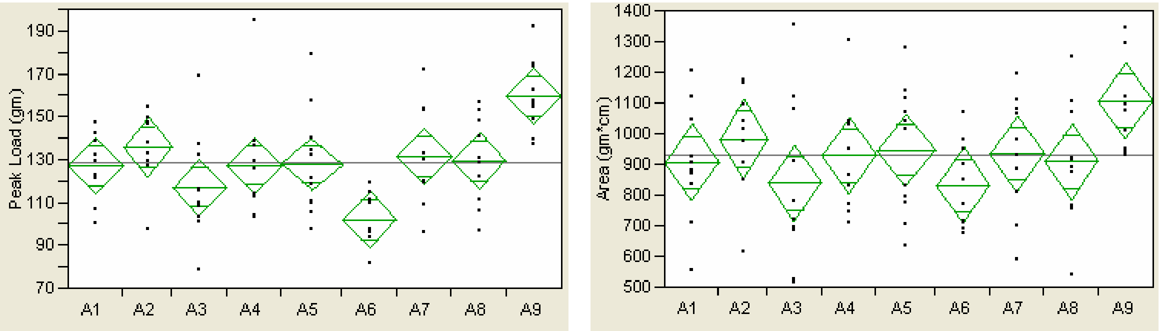
Table 11: RPT Trial 3 Data for Cylinder

		C Peak Load				C Area			
Type	**Style**	**Mean**	**Std Dev**	**n**	**Range**	**Mean**	**Std Dev**	**n**	**Range**
A	A1	133.4	13.1	4	25.7	1031.6	139.3	5	324.8
A	A2	141.6	12.0	4	28.1	1113.2	63.2	5	156.0
A	A3	127.3	28.0	4	60.4	1048.8	219.7	5	577.9
A	A4	134.0	40.8	4	82.3	1071.6	135.5	5	356.2
A	A5	134.9	19.5	4	47.1	1118.6	103.9	5	263.0
A	A6	98.0	15.8	4	38.0	933.3	109.3	5	296.0
A	A7	132.6	27.5	4	62.9	1086.6	77.1	5	213.0
A	A8	140.9	13.5	4	30.8	1047.2	147.4	5	360.3
A	A9	155.5	15.6	4	35.5	1195.5	171.9	5	406.4
B	B1	109.2	12.6	5	32.0	937.2	145.7	5	352.1
B	B2	97.7	28.2	5	66.6	815.5	110.2	5	263.3
B	B3	107.4	19.2	5	52.2	859.6	97.7	5	228.2
B	B4	95.8	15.6	5	37.9	786.4	66.7	5	168.0
B	B5	98.4	25.9	5	64.2	699.1	154.2	5	417.8
B	B6	101.2	17.7	5	46.1	832.6	88.2	5	225.3
B	B7	125.5	15.1	5	40.3	948.6	199.3	5	501.6
B	B8	133.8	26.2	5	67.5	1033.1	195.1	5	477.1
C	C1	278.9	32.5	5	68.6	1870.1	312.9	5	878.5
C	C2	583.2	151.7	5	384.4	3714.6	490.1	5	1119.7
C	C3	637.8	72.2	5	194.5	4454.3	220.8	5	504.4
D	D1	125.2	29.3	5	76.5	896.4	181.5	5	460.8
D	D2	279.4	64.8	5	156.6	1766.1	401.2	5	878.9
D	D3	318.3	89.7	5	243.3	2175.2	367.1	5	833.8
E	E1	362.6	61.0	5	154.4	2195.5	374.6	5	1022.4
E	E2	444.2	157.3	5	388.0	2624.0	760.8	5	1981.1
F	F1	646.0	66.2	5	183.1	2960.8	217.1	5	518.8
F	F2	1087.0	290.4	5	722.2	4561.4	1170.0	5	2854.9
F	F3	1012.1	188.0	5	374.6	4652.8	747.3	5	1843.9
F	F4	556.5	112.4	5	302.5	2758.6	363.3	5	883.5

For fabric A, C, and D we failed to reject the null hypothesis that the data was normal. Fabric B data displayed some non-normality. Of the categories Area by Cylinder, Peak Load by Cylinder, Area by Normal, Peak Load by Normal, we were able to reject the null hypothesis in all but Peak Load by Cylinder. All others had p-values less than 0.05. The same case was true with Fabric F, as the only case where we failed to reject the null hypothesis was Peak Load by Cylinder. For F, n=20 for all paired subgroups however.

For fabric E, Peak Load by Cylinder was found to be non-normal, though with a sample size of n=10 data points, this is likely to be due to the small sample size. This may be true for fabric F as well. The Central Limit Theorem states that a distribution of averages (n≥30) tends to be normally distributed. As sample size goes up, the distribution of the data tends to become more normal (3). Fabric B's non-normality is not in accordance with the Central Limit Theorem, as n=40 for all paired subgroups.

For fabric type A, the Bartlett's test statistic for variance displayed a p-value of greater than 0.05, so ANOVA was chosen for mean analysis. The results showed statistically significant differences in the peak loads of a few of the style types, however, it was not able to detect differences in terms of areas. Fabric A9, the washable, easy care style, displayed the highest peak load of the fabric type. Statistically significant differences were able to be detected between this style and two other styles, A3 (treated with Softener 1) and A6 (Softener 1 and 2).

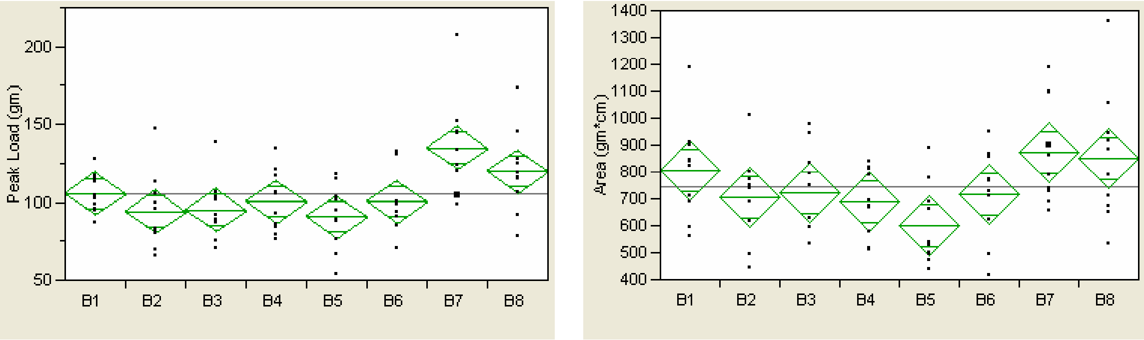


Prob>F = <.0001

Prob>F = <.0977

Figure 49: Fabric A Task 3 ANOVA

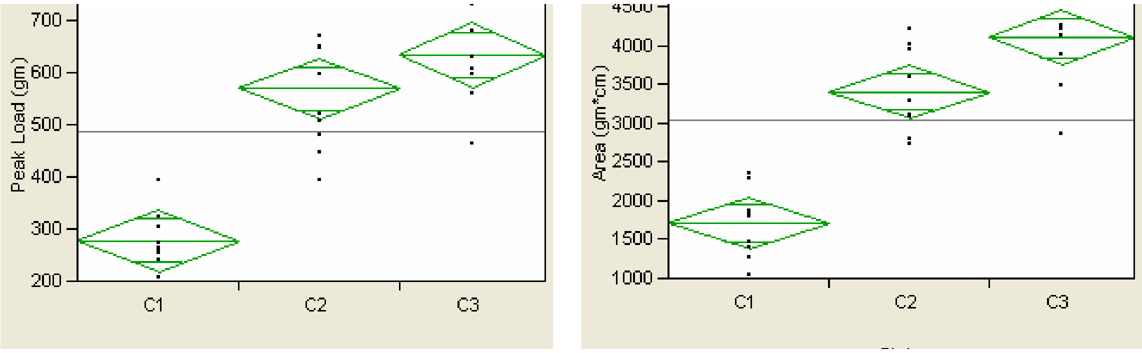
The variances of fabric B were analyzed using Levene's test statistic. Finding no statistical difference in the variances of the styles, nonparametric methods were used to test for mean. Statistically significant differences in peak load and area were detectible between styles using the 2.5 cm ring and cylinder. Significant differences exist between B7 (W/O Repel + Softener 1) versus B2 (Warp Stretch), B3 (Warp Stretch + Softener 1), B4 (Softener 2), B5 (Softener 1 and 2), and B6 (W/O Repel) in terms of peak load. Peak load differences can also be detected between B8 (Easy Care) versus B2, B3, and B5. In terms of area, B7 and B8 were found to have higher values than B5 (Softener 1 and 2), with moderate statistical difference between B1 (Control) and B5 as well.



Prob>ChiSquare = <.0021 Prob>ChiSquare = <.0423

Figure 50: Fabric B Task 3 ANOVA

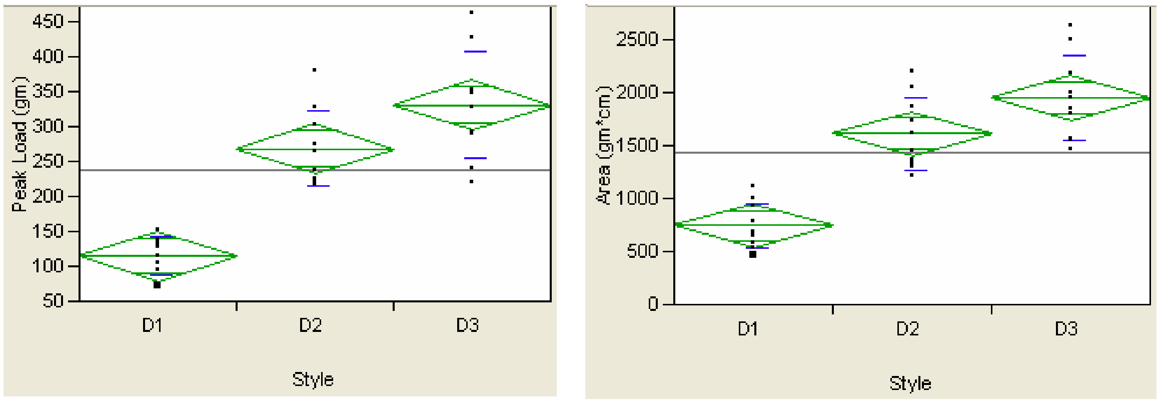
ANOVA was used to investigate the sample means of fabrics C and D. The ANOVA plot shows the means of the peak load and area values for the dyed fabric C1 to be statistically different, and lower, than the printed C2, and finally DWR-treated C3. A moderate statistical difference can be seen in the areas of C2 and C3, with C3 having a somewhat higher mean area. For fabric D, Welch's ANOVA was used to test means. The results of fabric D were consistent with those of C. The dyed type, D1, had significantly lower means and variances for peak load and area versus the printed and DWR-treated. Again, the mean values for peak load and area increase with successive treatments.



Prob>F = <.0001

Prob>F = <.0001

Figure 51: Fabric C Task 3 ANOVA

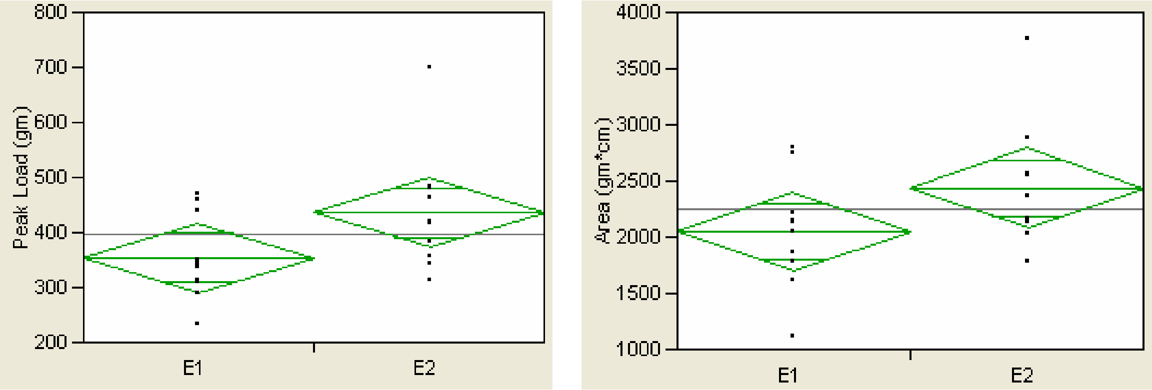


Prob>F = <.0205 (Bartlett's)

Prob>F = <.2115 (Bartlett's)

Figure 52: Fabric D Task 3 Welch ANOVA

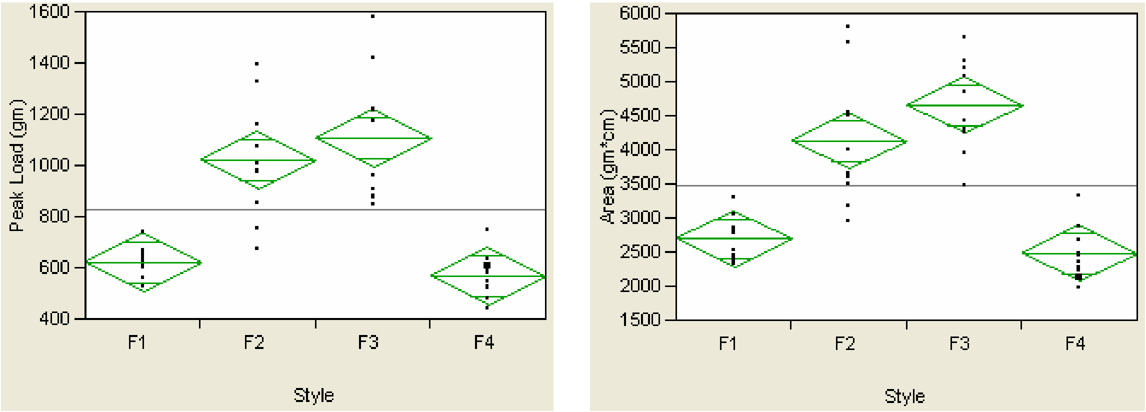
Levene's test statistic was used to test the variances of fabrics E and F. A moderate statistical significance between the two styles of fabric E was found, as the p-value of 0.0539 is on the cusp. In terms of area we fail to reject the null hypotheses that the sample means are the same for the area under the load-displacement curves of fabric E.



Prob>ChiSquare = <.0494 Prob>ChiSquare = <.1736

Figure 53: Fabric E Task 3 ANOVA

For fabric F, the Levene's test statistic found a statistically significant difference in variances for the four sample groups. The Wilcoxon nonparametric test shows that there is a difference in means. Styles F1 and F4 are not able to be differentiated, but they are different from the similar F2 and F3 styles. This is true for both peak load and area means.

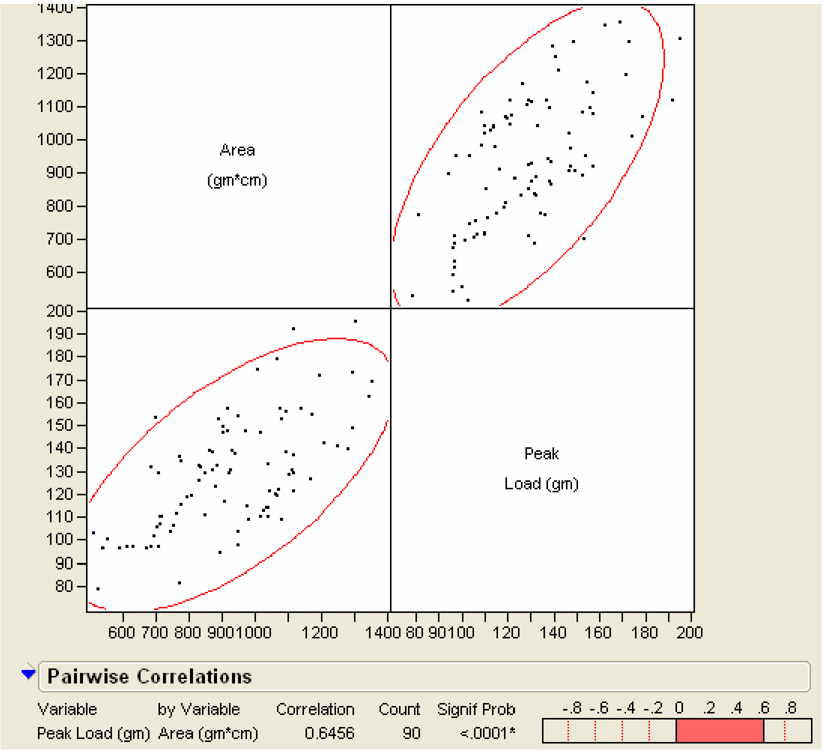


Prob>ChiSquare = <.0001 Prob>ChiSquare = <.0001

Figure 54: Fabric F Task 3 ANOVA

4.3.3.1 Analysis of Area and Peak Load Correlation

The correlation coefficient, r, quantifies the strength between two variables, with -1<r<+1. It depends on the process being studied whether an r value is sufficient. For some processes an r of 0.99, suggesting that one variable may predict 99% of the variation in the process, is needed. Often, in less understood processes, 0.65 is seen as a strong enough predictor (3). For fabric A, the correlation coefficient, r, for the relationship between area and peak load, was found to be 0.6456. This was the r value found with both normal ring and cylinder values included. Figure 55 shows the Pairwise Correlation Scatterplot Matrix, which was found to be significant.



Pairwise Correlations

Variable	by Variable	Correlation	Count	Signif Prob
Peak Load (gm)	Area (gm*cm)	0.6456	90	<.0001*

Figure 55: Fabric A Task 3 Pairwise Scatterplot of Area and Peak Load

When the ring values and the cylinder values were analyzed independently, we see different levels of correlation. When the fabric was pulled through the cylindrical ring, the r value was 0.6384. However, the correlation between area and peak load was much higher between the fabrics pulled through the normal (ring), with an r value of 0.8427.

For fabric B, the correlation coefficient, r, was found to be 0.6954 for the grouped normal and cylinder values. When the cylinder and normal values were not grouped, the r values went up, with a correlation of 0.7798 for the cylinder-only and 0.8342 for the normal ring-only. (See Appendix A Figures 65, 66).

The correlation coefficient between area and peak load for the combined cylinder and normal values is very high for fabric C, with an r value of 0.9185. The effect of ring versus cylinder in terms of r values was not as strong for fabric C, for the cylinder only had an r value of 0.9202, with normal only having an r of 0.9276. We are seeing, however, that as the number of styles within a fabric type goes down, the correlation coefficient is going up.

With normal and cylinder data grouped together, the correlation coefficient for area and peak load of fabric D was 0.8868. Individually, the r value was 0.7952 for cylinder data and a very strong 0.9603 for normal data, the highest correlation so far.

Very strong correlation coefficients existed within the E fabric type, which consisted of only two styles. The overall grouped r value was 0.9148. One difference with this fabric set, however, was that the cylinder grouping had a higher correlation coefficient than the normal ring grouping, though the actual difference was not substantial (0.9561 versus 0.9065).

Similar to fabric E, the r values of fabric F were very strong and uniform across both cylinder and normal ring data. A combined r value of 0.9311was the strongest of all of the fabric types, suggesting a very strong relationship between area and peak load. There was very little difference between cylinder and ring values as well, with these being 0.9617 and 0.9560 respectively (See Appendix A Figure 67).

4.3.4 Task 4

Task 4 consisted of a DOE for crosshead speed of the MTS tensile tester using one fabric style each from three fabric types (A, D, F).The DOE was set up similarly to that of Task 2, with a range of ring diameters and both ring shapes being used, however, with the addition of two new crosshead speeds. Three speeds were used (15 in/min, 20 in/min, and 25 in/min) to see the effect of pulling speed on fabric peak load values. A crosshead speed of 20 in/min was chosen as the median based on the previous research of Grover, Sultan, and Spivak (13) and more recently by Heidi Steckert (30).

Table 12: RPT Trial 4 Data for Normal Ring

		N Mean Peak Load (gm)			N Std Dev			n	N Range		
Type	Style	15 in/min	20 in/min	25 in/min	15 in/min	20 in/min	25 in/min		15 in/min	20 in/min	25 in/min
A	A1	106.3	119.3	113.4	99.9	88.4	116.4	24	284.7	246.5	293.4
D	D1	53.9	62.1	69.4	32.9	37.2	45.0	18	81.7	95.7	119.5
F	F1	721.2	786.8	694.4	264.8	233.7	153.7	18	495.3	740.3	337.1

Table 13: RPT Trial 4 Data for Cylinder

		C Mean Peak Load (gm)			C Std Dev			n	C Range		
Type	Style	15 in/min	20 in/min	25 in/min	15 in/min	20 in/min	25 in/min		15 in/min	20 in/min	25 in/min
A	A1	135.7	156.0	150.1	136.5	128.7	158.7	24	367.8	362.3	447.5
D	D1	72.1	55.9	82.0	39.4	33.1	52.3	18	90.2	78.8	126.7
F	F1	812.7	810.5	834.5	196.1	262.7	269.0	18	421.9	688.5	576.5

Vertical bar charts of the mean peak load data for all three fabric types are shown in Figure 56. There appears to be no significant difference in peak load due to crosshead speed for all three fabric types.

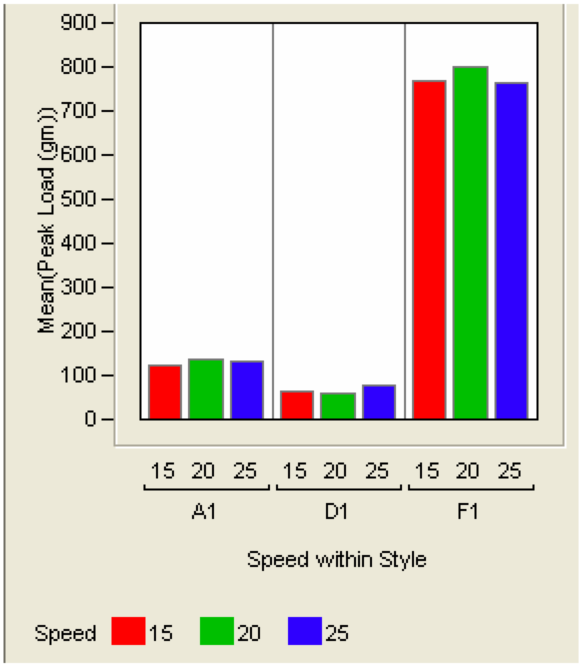
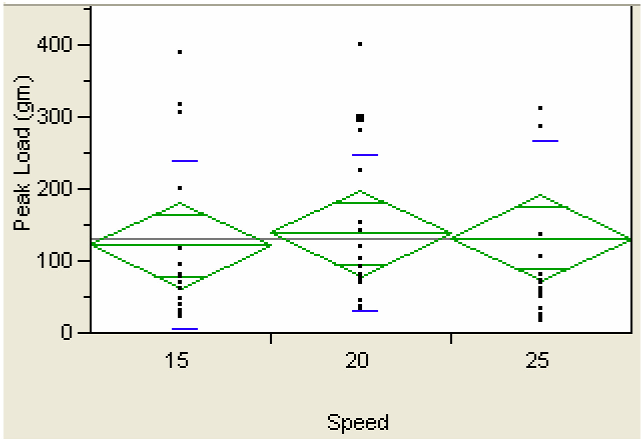


Figure 56: Mean Peak Load by Crosshead Speed and Style

Peak load was found to be moderately non-normal across fabrics A, D, and F. After checking for normality using the p-values from the Goodness-of-Fit Tests, the variance of the three populations for each fabric type were tested using Levene's test statistic. Next nonparametric methods were used to test the means of the sample groups. Using JMP, a Wilcoxon/Kruskal-Wallis Test was performed for each of the fabric types.

Chi p-values show that we fail to reject the null hypothesis that the sample means are the same for all three speeds. Apparently there is no statistically significant difference in peak load based on variation in pulling speed through the ring or cylinder within these limits of speed. This is true across all three fabric types.



Prob>F = <.6510 (Levene's)

Figure 57: Task 4 Peak Load by Crosshead Speed-Fabric A

4.3.5 Task 5

Task 5 consisted of the same procedure as Task 1, the 20 repetition trial on all appropriate ring diameters. The difference, however, is that in Task 5 samples were not pre-folded as they were in all other trials. Fabric samples rested on the operator's palm, lying flat, until the crosshead began to pull upwards, at which point the hand was removed and the fabric was free to fold and twist at will. The peak loads of these load-displacement curves were analyzed versus those of Task 1.

Table 14: RPT Trial 1 and 4 Data

		N Mean Peak Load (gm)		N Std Dev		n		N Range	
Type	**Style**	**Folded**	**Freeform**	**Folded**	**Freeform**	**Folded**	**Freeform**	**Folded**	**Freeform**
A	A1	146.8	142.7	128.9	124.3	80	80	453.6	426.8
D	D1	110.2	172.0	101.1	138.6	80	80	345.1	441.2
F	F1	674.0	638.7	168.4	229.9	40	40	647.6	1018.5

Vertical bar charts of the mean peak load data give an initial estimation of the effect of the mounting procedure on the three fabric types. Fabrics A and F appear to be relatively unaffected by whether the fabric was pre-folded or not. The mean peak loads for fabric D, on the other hand, show freeform values to be higher across all ring diameters.

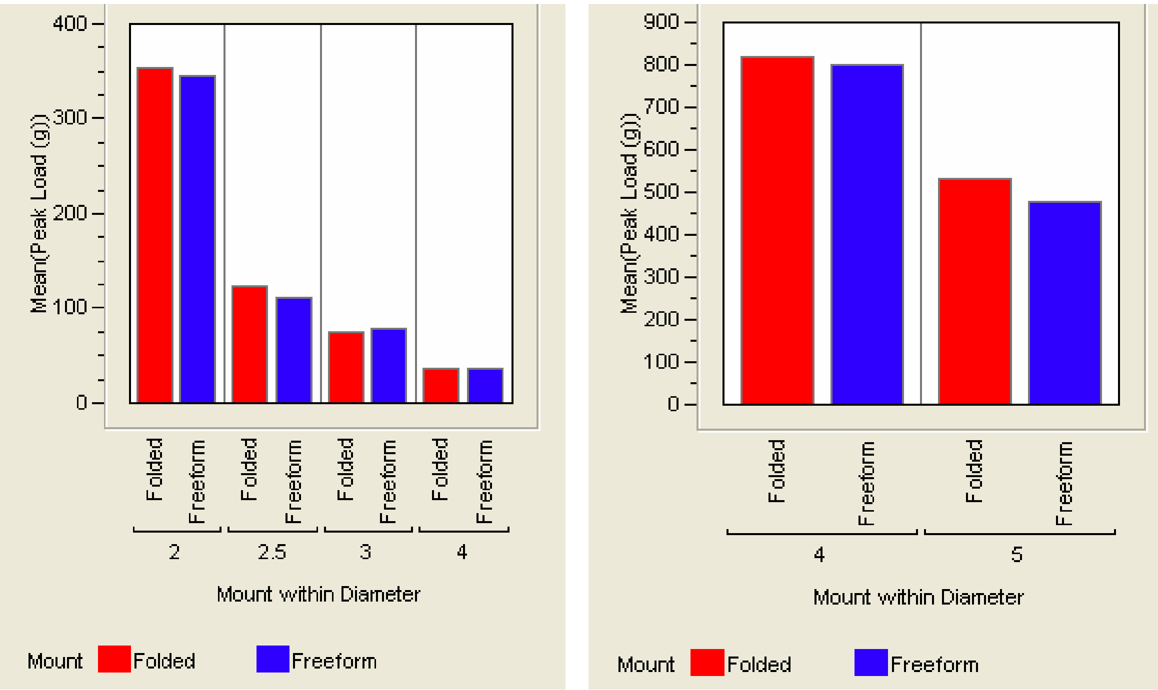


Figure 58: Mean Peak Load by Mounting Procedure-Fabric A (left), F (right)

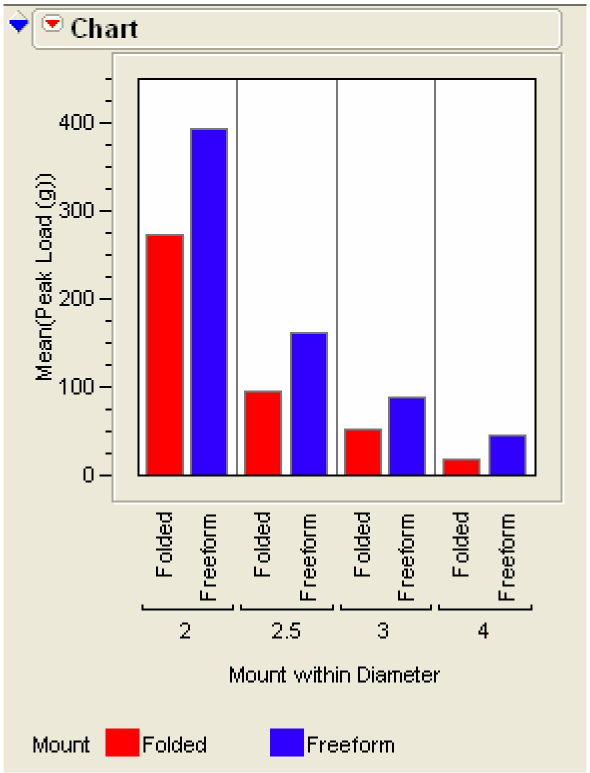
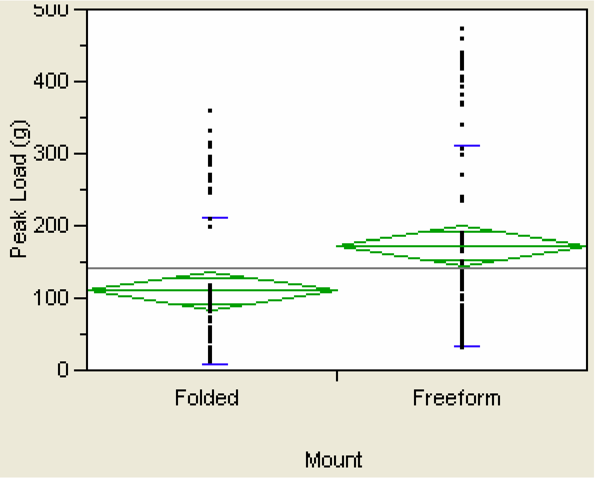


Figure 59: Mean Peak Load by Mounting Procedure-Fabric D

Since the analysis was segmented by fabric type (A, D, F), a two sample analysis was performed (folded versus freeform). Since the data showed that we were able to reject the null hypothesis that the data was normal, the variance of the two populations was tested using Levene's to generate an F test statistic. The F test is the ratio of the two variations from sample groups one and two, with the null hypothesis being that the two variations are the same (3). In addition, nonparametric methods were used to test group means.

The high p-values for fabric A show that you cannot reject the null hypothesis that either the variances (Levene's) or the means (Wilcoxon) are the same for both the folded and freeform peak loads. The same is true for fabric F. Fabric D, on the other hand, displays a significant difference in both the variance and the means of the two sample groups, with p-values less than 0.05. This suggests that for some fabrics, the mounting procedure is a source of variation.



Prob>F = <.0031 (Levene's)

Figure 60: Levene's Peak Load by Mounting Procedure-Fabric D

Photos and video taken during Trial 5 showed the most exaggerated folding behavior being exhibited by fabric D in relation to A and F. Using the freeform mounting procedure, visibly many folds were created in the fabric as it distorted itself through the ring (See Figure 61).

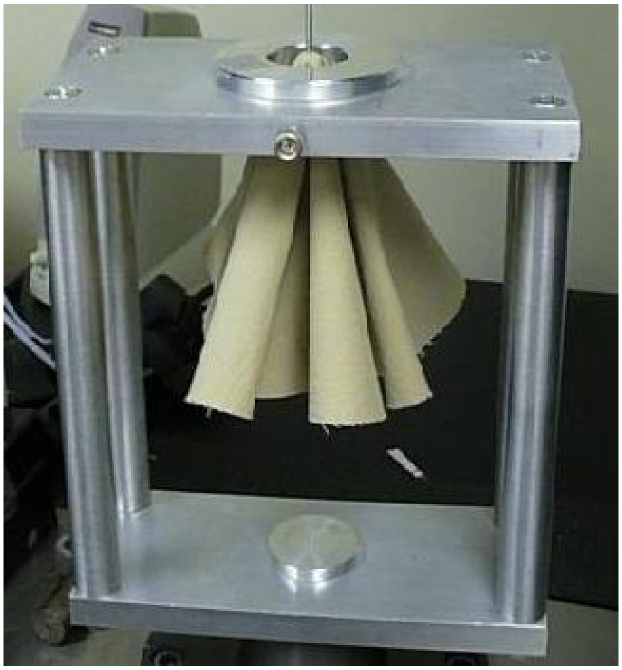


Figure 61: Fabric D Freeform Mounting Procedure Run

4.4 Test Methods Comparison using Multiple Regression

4.4.1 Subjective, FAST, and RPT Regressions

In these regression models, the six categories of subjective hand evaluation data serve as the dependent variables, with y = End Use Preference, Comfort, Compression, Extension, Bending or Surface. Not all of the six subjective parameters were represented for all fabric types, as the logistic regression odds ratios for these parameters were used as the basis of comparison. As it was found that not all subjective parameters were statistically significant based on logistic regression, only the odds ratios for the significant parameters were used as a the dependent variables.

As seen in the tables, often more than one model was created to explain the dependent variables. In a situation where there was so much collinearity between test parameters, this was an attempt to find all regressor combinations that were useful at explaining the dependent variables. Therefore additional models that were found to be statistically significant were included for each of the y values. Stepwise regression models were run until the author felt that all useful combinations had been reported.

The pool of potential regressors for these models included all 25 FAST variables and four RPT variables, N Ave PK Load, C Ave Peak Load, N Ave Area, C Ave Area. The “N” and the “C” correspond to the ring shape, normal or cylinder. These results were derived from RPT Trial 3.

Table 15: Subjective, FAST, RPT Regression Models

Type	y	β_0	β_1	X1	β_2	X2	β_3	X3	R-2
A	End Use	-47.7	0.94	HE-1 !	0.3	W >	-0.04	N PkLoad $	0.91
A	End Use	20.6	-3.5	E5-2 #	-0.1	C-2 ?	-414.2	ST @	0.97
A	Comfort	-47.7	0.94	HE-1 !	0.3	W >	-0.04	N PkLoad $	0.91
A	Compress	-285.9	-0.5	RS-1 !	1.6	EB5 #	127.7	T100R @	0.78
A	Compress	-254.1	1.56	EB5 #	112.8	T100R @			0.69
A	Extension	6	-1.27	E5-2 #	0.02	C-2 ?	-0.19	G %	0.76
A	Extension	-1.58	-0.8	E20-2 #	0.92	EB5 #			0.66
B	End Use	2.4	-2.2	HE-1 !	8.6	F-1 %			0.96
B	End Use	-22.3	3.8	E20-1 #	1.6	C-1 ?	-0.6	C-2 ?	0.93
B	Comfort	1028.6	-4	HE-1 !	18.7	F-1 %	-473.9	T100R @	0.97
B	Comfort	-42.4	7.6	E20-1 #	2.7	C-1 ?	-0.9	C-2 ?	0.87
B	Extension	19.52	-2.4	E20-2 #	-27.1	ST @	-0.02	C Area X	0.98
B	Extension	362.4	-199.8	T2 @	36.3	T100 @			0.81
B	Bend	21.5	-0.4	C-2 ?	0.26	C PkLoad $	-0.05	C Area X	0.9
C,D	End Use	4.8	-0.08	B-2 ?					0.99
C,D	End Use	6	-0.002	C Area X					0.99
C,D	Comfort	97.6	-12.5	C-1 ?	1.9	W >			0.99
C,D	Comfort	-0.197	-24.7	F-1 %	78.3	E20-1 #	-0.08	B-2 ?	0.99
C,D	Compress	3.7	-0.006	N Pk Load $					0.99
C,D	Compress	5.7	-0.17	C-2 ?					0.99
C,D	Extension	0.0004	0.03	E20-2 #					0.99
C,D	Bend	1E+07	897749	E5-2 #	-551810	C-1 ?	151968	B-1 ?	0.99
C,D	Surface	23907	-296	E100-1 #	-994.9	C-1 ?	161.2	B-1 ?	0.99
C,D	Surface	-233.9	-529.1	F-1 %	1793.2	E20-1 #	125.5	EB5 #	0.99
E,F	Comfort	19.8	-48.4	E20-1 #	70.4	EB5 #	-1087	STR @	0.99
E,F	Comfort	19.95	-63.1	HE-1 !	454.8	E5-2 #	0.05	W >	0.99
E,F	Extension	-20.3	2.4	E20-2 #	16.1	E100-1 #	0.26	C-1 ?	0.99
E,F	Extension	1601.8	-0.02	C Pk Load $	1.6	F-2 %	-732.9	T100R @	0.98
E,F	Bend	-0.14	0.15	RS-2 !	0.05	F-1 %	0.21	F-2 %	0.99
E,F	Bend	-1.07	0.001	C Pk Load $	1.2	E100-1 #			0.98
E,F	Surface	274	-0.08	E100-1 #	-97.6	T100 @	-27.6	T2R @	0.99

Test	Parameter	Color	Frequency	(+) coef	(-) coef
FAST 3	Extension	#	22	15	7
FAST 2	Bending	?	16	6	10
FAST 1	Thickness	@	11	3	8
FAST 2,3	CombBend/Ext	%	8	5	3
FAST 4	Dimension Stability	!	7	3	4
RING	Pk Load	$	6	2	4
N/A	Weight	>	4	4	0
RING	Area	X	3	0	3

Fabric types C, D and E, F were grouped so as to give more strength to the regression models (larger sample size). The models show that extension values from FAST-3 are the most useful for explaining subjective preference data.

These extension values were predominantly positively-correlated with the subjective rankings. It appears that as extension values go up for a style, the style is given more favorable subjective rankings, more so than any other parameter. Out of the 22, shown, 9 of these were at the 20 gf/cm load level. EB5, a bias extension parameter that is used to derive shear rigidity, was used 5 times.

Bending parameters such as C and B were the second most useful regressor category; however, overall, bending values such as bending length and bending rigidity were negatively correlated with favorable subjective rankings. Thickness was generally negatively correlated with subjective parameters.

It is important to note that both RPT peak load and area values were found to be, on average, negatively correlated with subjective preferences. As peak load and area values rise, the respondents were giving lower ratings for hand and comfort.

To find out more information about the mechanical properties that the RPT data is correlated with, regressions models were created for the RPT and FAST.

4.4.2 RPT and FAST Regressions

The dependent variables in these regressions are the four RPT parameters. The independent variables are the 25 FAST variables. Table 16 shows the regression models:

Table 16: RPT, FAST Regressions

Type	y	β_0	β_1	X1		β_2	X2		β_3	X3		R-2
A	N PkLoad	341.7	-38.63	**HE-2**	!	-2.75	**F-1**	%	-24.7	**E5-1**	#	0.868
A	N PkLoad	386.15	-27.8	**E5-1**	#	-16.3	**E100-2**	#	-20.9	**EB5**	#	0.7
A	C PkLoad	205.89	-26.6	**RS-1**	!	24.6	**E5-2**	#	-10.5	**EB5**	#	0.84
A	C PkLoad	-267.7	-62.4	**HE-2**	!	37.37	**E100-2**	#	2.33	**W**	>	0.89
A	N Area	-687.1	-281.7	**HE-2**	!	77.9	**E100-2**	#	12.6	**W**	>	0.98
A	N Area	1015.1	-114.3	**RS-1**	!	-57.4	**E100-2**	#	17.7	**G**	%	0.91
A	C Area	1748.6	-115.7	**RS-1**	!	-17306	**STR**	@				0.7
B	N PkLoad	-5603	-193.1	**E5-1**	#	25.1	**EB5**	#	2579.3	**T2**	@	0.966
B	C PkLoad	266.5	-41.4	**RS-2**	!	12.2	**HE-2**	!	-31.6	**E100-2**	#	0.96
B	C PkLoad	176.1	-55.7	**E5-2**	#	-8.7	**E100-1**	#	-1.5	**E100-2**	#	0.96
B	N Area	2252.9	-55	**E100-1**	#	-165	**E100-2**	#	-15.5	**G**	%	0.84
B	N Area	-40753	-982.9	**E5-1**	#	202.8	**E20-1**	#	18843	**T2**	@	0.95
B	C Area	-21369	-25.74	**E100-1**	#	-107.1	**E100-2**	#	10398	**T2**	@	0.99
B	C Area	-36042	-386.8	**E5-1**	#	-124.4	**E20-2**	#	16918	**T2**	@	0.93
C,D	N PkLoad	13115	21	**C-2**	?	-6398.7	**T100**	@	5	**W**	>	0.99
C,D	N PkLoad	54641	-25.2	**E100-2**	#	-24411	**T2R**	@				0.89
C,D	C PkLoad	207.2	-145.6	**RS-1**	!	-54	**E20-1**	#	9.2	**B-2**	?	0.99
C,D	C PkLoad	-665.3	-7.8	**E100-2**	#	19.7	**C-2**	?	20884	**ST**	@	0.99
C,D	N Area	60913	133.6	**C-2**	?	-31189	**T100**	@	41	**W**	>	0.99
C,D	N Area	377976	-154.2	**E100-2**	#	-169134	**T2R**	@				0.94
C,D	C Area	74890	145.7	**C-2**	?	-37763	**T100**	@	44.9	**W**	>	0.99
C,D	C Area	426900	171	**E100-2**	#	-190959	**T2R**	@				0.93
E,F	N PkLoad	26208	-822.4	**EB5**	#	18.3	**C-1**	?	-12098	**T100**	@	0.99
E,F	N PkLoad	102512	329.3	**E5-1**	#	-385.3	**E100-1**	#	-46877	**T100**	@	0.99
E,F	C PkLoad	-153.2	-669.1	**EB5**	#	17.1	**C-1**	?				0.94
E,F	C PkLoad	245017	-301.3	**HE-2**	!	-1089.4	**E5-2**	#	-1E+05	**T100R**	@	0.99
E,F	N Area	206682	2204.1	**E5-1**	#	47.7	**C-1**	?	-95220	**T100R**	@	0.94
E,F	N Area	-77727	671.6	**HE-2**	!	-1893.5	**E100-1**	#	36872	**T2R**	@	0.99
E,F	C Area	-144.8	-1743.4	**EB5**	#	67.7	**C-1**	?				0.98
E,F	C Area	215585	157.4	**F-2**	%	-1823.4	**E100-1**	#	-97539	**T100R**	@	0.95

Test	Parameter	Color	Frequency	(+) coef	(-) coef
FAST 3	Extension	#	37	8	29
FAST 1	Thickness	@	18	6	12
FAST 4	Dimension Stability	!	11	2	9
FAST 2	Bending	?	9	9	0
N/A	Weight	>	5	5	0
FAST 2,3	CombBend/Ext	%	4	2	2

Similar to the findings of the subjective regressions, values for extension are the most frequent independent variables used to describe the y variables of peak load and area. The coefficients of these extension regressors are predominantly negative, meaning that extension values are negatively correlated with peak load and area values. The opposite is again true of bending values, the second most frequent variable. Bending terms (C, B) are in all instances positively correlated with peak load and area values. In some cases, warp-direction bending length and rigidity values play a greater role in describing the peak load and area data (E, F), and in others, weft values (fabric C, D). It is important to note that the small load E5 values are the least strong of all of the extension values. These values may have a lot of error (positive values), with less significant differentiation between styles, given the stable woven fabrics of the sample set.

When looking at the multivariate scatterplot matrices for fabrics A and B, there appears to be collinearity between the dimensional stability (HE, RS) values and the extension values and the relationships of extension and dimensional stability to peak load and area are both negatively correlated. Efforts were made to avoid this collinearity in the regression models as much as possible, but it appears that the effect of finish on both of these fabric types is one on both extension and dimensional stability, and that this manifests itself in higher peak load and area values.

4.4.3 Subjective and RPT Regressions

The six subjective parameters serve as the y dependent variables in these regressions, with the four RPT parameters as the potential x, or independent variables.

Table 17: Subjective, RPT Regressions

Type	y	β_0	β_1	X1	β_2	X2	β_3	X3	R-2
A	End Use	15	-0.01	**N Area 3** >	0.002	**C Area 2** #	-0.004	**C Area 3** #	0.99
A	Comfort	15	-0.01	**N Area 3** >	1.002	**C Area 2** #	0.996	**C Area 3** #	0.99
A	Compress	5.3	-0.03	**N Peak 4** $	-0.004	**N Area 3** >	0.02	**C Ave PkLd** %	0.83
A	Extension	1.8	-0.01	**N Peak 4** $	0.008	**N Area 2** >	-0.007	**N Ave Area** <	0.79
B	End Use	3.96	-0.03	**N Peak 4** $	0.02	**N Area 3** >	-0.12	**C Peak 1** @	0.99
B	Comfort	5.3	0.3	**N Peak 3** $	-0.3	**C Peak 1** @	0.008	**C Area 2** #	0.98
B	Extension	8.8	0.02	**N Area 5** >	-0.02	**C Area 1** #	-0.004	**C Area 2** #	0.91
B	Bend	4.6	0.07	**N Peak 3** $	-0.01	**C Area 5** #			0.87
C,D	End Use	5.1	-0.007	**N Peak 5** $					0.99
C,D	Comfort	50.15	-0.81	**C Peak 1** @	0.72	**C Ave PkLd** %			0.99
C,D	Compress	3.4	-7E-04	**C Area 1** #					0.99
C,D	Extension	0.035	-8E-08	**C Area 4** #					0.99
C,D	Bend	1E+06	-17407	**C Peak 1** @	15694	**C Ave PkLd** %			0.92
C,D	Surface	1318.1	-21.8	**C Peak 1** @	19.6	**C Ave PkLd** %			0.93
E,F	Surface	2.2	0.0014	**N Area 2** >	-0.002	**C Area 4** #			0.94

Test	Parameter	Color	Frequency	(+) coef	(-) coef
TASK 3	C Area	#	11	4	7
TASK 3	N Area	>	7	4	3
TASK 3	N Peak	$	6	2	4
TASK 3	C Peak	@	5	0	5
TASK 3	C Ave PkLoad	%	4	4	0
TASK 3	N Ave Area	<	1	0	1
TASK 3	N Ave PkLoad	!	0	0	0
TASK 3	C Ave Area	X	0	0	0

Overall these regression models support the previous sets of models in their finding that there is a stronger negative relationship than a positive between subjective preferential ranking data and RPT peak load and area. There is a lot of collinearity in the above RPT variables, as we saw in the ring results (strong correlation coefficients between peak load and area). There are a few trends worth noting, however. Cylinder values for area and peak load appear to be more indicative of subjective data than the normal ring, especially for fabrics C, D.

Now that the results from both the subjective and objective testing have been analyzed individually and together via multiple regressions, the overall findings will be discussed in the following chapter.

CHAPTER V

5 Discussion and Recommendations

5.1 Test Method Conclusions

The FAST system was found to have valuable information, though a large portion of this was redundant, as seen by the Principal Component Analysis. Additionally, the multivariate scatterplot matrices in Appendix B show a great deal of collinearity between FAST variables. In particular, FAST-3 extension values are very highly correlated to a number of other variables such as relaxation shrinkage, hygral expansion, and formability. Dimensional stability and extension correlations are especially true with the worsted suiting sets (fabrics A, B).

In terms of graphical analysis tools for the FAST data, the traditional snake plot control chart was thrown out as it is geared to tailoring operations, and the raw data was analyzed in the form of radar plots and PCA bi-plots. It was found that there are many issues to using radar plots as a tool for evaluating FAST data. One is that the data has to be normalized. A few errant data points can lead to skewed results. Care needs to be taken to screen the data and find ways to eliminate insignificant variation. Another shortcoming of radar charts is that the plots change based on the ordering of the test variables along the 25 different axes. A new order would change the up and down movement of the style lines as they travel along the different axes. Additionally, the style lines were jumbled with fabrics A, B, and F. Beyond three styles per radar plot makes it is difficult to assess the movement of each fabric style along the axes, and where each of these fall. Therefore, it is suggested that radar plots only be used if there are three or less styles to compare within a sample grouping.

Beyond these difficulties, there were some findings from the radar plots. Styles A9 and B8, the easy care styles, were both in the bottom of their type in terms of extension values. These styles also had high values for shear rigidity. The radar plot for fabric F shows that F4 had the highest extension.

In the subjective rankings, extension appeared to be the main differentiator, as the easy care (found to have the lowest extension ratings with the radar plots) had the lowest mean scores in terms of comfort, and the warp stretch styles had the highest. This is true for the F fabric grouping as well, with F4 obtaining the highest ratings.

The Principal Component Analysis bi-plot was a more effective graphical tool for obtaining a quick snapshot of the fabric type groupings. It is important to note that PCA is effective for gaining insight into which fabrics are behaving similarly and which are behaving differently, with respect to all of the test parameters. This tool does not allow us to say that one fabric is more comfortable than another; through it could be a powerful tool for development in that it shows differences that could be further subjects of investigation.

In terms of showing differences, the PCA bi-plots line up well with the subjective comfort plots. For fabrics A and B, we are seeing that the easy care and the warp stretch fabrics are being isolated from the group. For C and D, the strong differential between C1 and D1 versus the other two styles in their respective groups is evident in these plots as it was in the comfort plots. Finally, the bi-plot of E, F shows that the style F4 is much more in line with E1 and E2 than the rest of the styles in its group, again reflecting the change in extension and bending values.

In the Ring Pull-Through analysis, a strong correlation between area and peak load values was shown. This suggests that only one of these variables is necessary for analysis. However, in the Subjective and RPT Regression Models, it was found that the cylinder peak load and area values were more indicative of the subjective rankings, presenting a case for using cylinder values as a more significant reflection of human preference. Further research could include an analysis of fabrics via the peak load value obtained from the normal ring pull-through in conjunction with the area values of an extended depth cylinder.

Besides peak load and area, the coefficient of variation of the means of the curves could be used as an additionally metric for analysis. The coefficient of variation could potentially give more information about the shape of the curve, perhaps alluding to multiple peaks. Such curves could have the same peak load and area under the curve, but a different coefficient of variation.

In terms of crosshead speed, there was no statistically significant difference in peak load between the three speeds analyzed in this research. Given that limits were set on the MTS used in this research to not go beyond 25 in/min, it can be asserted that variation in crosshead speed is not a valuable source of new information for RPT trials.

A statistically significant difference in peak load values based on mounting procedure was found with one fabric style, fabric D. This fabric type showed larger peak load and area values for samples pulled through ring diameters using the freeform mounting procedure, wherein circular specimens are not pre-folded prior to pulling. A more exaggerated folding behavior was exhibited with this fabric type in relation to the other fabric types. In future trials, such a mounting procedure trial should be performed with all new sample sets in order to see the extent to which this variable will come into play during trial runs.

5.2 Research Objectives Revisited

RO1: To identify a few potential methods that could serve as alternatives to KES-F in the objective measurement of fabric hand.

- Identified CSIRO Fabric Assurance by Simple Testing and a Ring Pull-Through Method

RO2: To conduct fabric hand evaluation trials on appropriate sample sets using these methods.

- Acquired six woven fabric types and performed a subjective fabric hand evaluation for all styles within these six types

RO3: To develop these simple methods into more effective tools for the objective measurement of fabric hand.

- Conducted trials to develop the methods and chose appropriate statistical analysis tools to explore ways of communicating result information

RO4: To compare these methods with a subjective assessment.

- Objective test parameters were compared to subjective rankings via multiple regression analysis

RO5: To construct a matrix, or methodology, that incorporates these methods to use as the basis for a larger comfort measurement system.

- The final stage of the research

5.3 Comfort Measurement Matrix

The aim of this research was to provide industry with an additional metric whereby decisions can be made based on values for fabric hand and comfort. The goal was that this method would provide a high speed and low cost alternative to the currently available methods, such as subjective assessments and the Kawabata Evaluation System. Though there is still work to be done in terms of the development of these methods (particularly the Ring Pull-Through), there are some clears trends that emerge.

The Ring Pull-Through method is a promising system that has been found to be capable of the level of fabric discrimination characteristic of human judges in a subjective evaluation. The RPT device does not at this point have the ability to make minor distinctions between fabrics with any consistency; however, the results show that the RPT resolution was high enough to discern outliers and style ordering relationships to the same extent as the subjective evaluation.

Strong relationships were shown between the FAST-3 extension results and both the subjective rankings and RPT peak load and area data. The hand and comfort measurement method could be further refined by including a test for extension. The test for extension, or ease of extensibility, would not have to include the purchase of a FAST system, but rather a simplified test of extension under various loads would be sufficient. This could be a stand-alone device or another sort of attachment piece in the same vein as the RPT device.

Used together, the Ring Pull-Through method and the FAST-3 Extension Meter or other simplified extension test are two potentially very promising techniques that give some clear insight into the direction that we should be going in terms of the development of a simplistic, low cost test method. The current research points to this system being of sufficient sensitivity to reflect changes that can be detected by subjective evaluations, yet basic enough to suit the manufacturing setting.

To develop a matrix, or visual tool that would incorporate the results from these two chosen methods (RPT and FAST-3 extension values), the data was pooled in a worksheet format and a number of statistical parameters were tabulated, namely sample mean, standard deviation, variance, range and n, sample size. Based on these values, additional parameters were calculated to form the framework of the matrix. Efforts began with the two suiting fabrics, A and B. Shown in Tables 18 and 19 are the tabulated data tables for fabrics A and B.

Table 18: Tabulated Data for Matrix-Fabric A

Test Statistic	Fabric A												
	A1	A2	A3	A4	A5	A6	A7	A8	A9	A All Styles	A Median		
Wt. (g/m^2)	175	182.5	177.5	177.5	182.5	176.7	175	172.5	182.5	178.0	177.5		
# Styles										9	9		
FAST-3													
E5-1 (%) Mean	0.9	0.8	0.4	1.4	0.7	1.0	0.5	0.9	0.7	0.8	0.8		
Std. Dev.	0.3	0.1	0.3	0.2	0.2	0.6	0.2	0.3	0.3		0.3		
Variance	0.1	0.0	0.1	0.0	0.0	0.4	0.0	0.1	0.1		0.1	0.2	se
Range	0.5	0.1	0.6	0.3	0.3	1.2	0.4	0.5	0.6		0.5	18.0	df
n	3	3	3	3	3	3	3	3	3		3.0	2.445006	tcritical
												0.434668	dmin
												0.217334	bwidth
E5-2 (%) Mean	1.2	1.0	1.4	1.0	1.0	0.9	0.8	1.5	1.0	1.1	1.0		
Std. Dev.	0.6	0.3	0.6	0.6	0.4	0.3	0.3	0.1	0.4		0.4		
Variance	0.3	0.1	0.3	0.3	0.1	0.1	0.1	0.0	0.1		0.1	0.2	se
Range	1.1	0.5	1.1	1.1	0.7	0.5	0.6	0.2	0.7		0.7	18.0	df
n	3	3	3	3	3	3	3	3	3		3.0	2.445006	tcritical
												0.571794	dmin
												0.285897	bwidth
E20-1 (%) Mean	1.6	2.1	0.9	2.5	1.8	2.0	1.1	1.7	1.5	1.7	1.7		
Std. Dev.	0.5	0.1	0.5	0.1	0.2	0.7	0.3	0.5	0.5		0.5		
Variance	0.2	0.0	0.2	0.0	0.0	0.5	0.1	0.2	0.2		0.2	0.2	se
Range	0.9	0.1	0.9	0.2	0.3	1.3	0.5	0.9	0.9		0.9	18.0	df
n	3	3	3	3	3	3	3	3	3		3.0	2.445006	tcritical
												0.578211	dmin
												0.289106	bwidth
E20-2 (%) Mean	3.2	2.8	3.6	2.7	2.8	2.5	2.6	3.5	2.5	2.9	2.8		
Std. Dev.	0.7	0.2	0.5	0.7	0.4	0.3	0.5	0.2	0.4		0.4		
Variance	0.4	0.1	0.2	0.5	0.1	0.1	0.3	0.0	0.2		0.2	0.3	se
Range	1.3	0.4	0.9	1.3	0.7	0.6	1.0	0.3	0.8		0.8	18.0	df
n	3	3	3	3	3	3	3	3	3		3.0	2.445006	tcritical
												0.645174	dmin
												0.322587	bwidth
E100-1 (%) Mean	2.9	5.2	2.3	5.1	4.6	4.6	2.8	3.8	3.7	3.9	3.8		
Std. Dev.	0.6	0.1	0.7	0.2	0.2	1.0	0.4	1.3	0.9		0.6		
Variance	0.4	0.0	0.4	0.0	0.0	1.1	0.1	1.8	0.8		0.4	0.4	se
Range	1.2	0.2	1.2	0.4	0.3	1.9	0.7	2.5	1.8		1.2	18.0	df
n	3	3	3	3	3	3	3	3	3		3.0	2.445006	tcritical
												1.017937	dmin
												0.508969	bwidth
E100-2 (%) Mean	7.9	7.3	9.4	7.5	7.6	7.3	7.4	8.4	6.9	7.7	7.5		
Std. Dev.	0.6	0.3	0.4	0.9	0.2	0.3	0.9	0.2	0.6		0.4		
Variance	0.3	0.1	0.2	0.8	0.0	0.1	0.7	0.0	0.3		0.2	0.3	se
Range	1.1	0.6	0.8	1.8	0.4	0.5	1.7	0.3	1.1		0.8	18.0	df
n	3	3	3	3	3	3	3	3	3		3.0	2.445006	tcritical
												0.760668	dmin
												0.380334	bwidth
EB5 (%) Mean	5.4	6.1	5.5	4.9	5.6	5.5	5.8	5.1	4.5	5.4	5.5		
Std. Dev.	0.6	1.0	0.5	0.5	0.8	0.4	0.6	0.4	0.4		0.5		
Variance	0.3	0.9	0.3	0.2	0.6	0.2	0.3	0.2	0.1		0.3	0.2	se
Range	1.8	2.2	1.3	1.1	1.6	1.2	1.4	1.2	1.0		1.3	45.0	df
n	6	6	6	6	6	6	6	6	6		6.0	2.318891	tcritical
												0.558908	dmin
												0.279454	bwidth
RPT Procedure													
Ring Diameter (cm)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5		
Mounting Req. (Y/N)	N	N	N	N	N	N	N	N	N	N	N		
Crosshead Req. (Y/N)	N	N	N	N	N	N	N	N	N	N	N		
RPT Output													
N Peak Load (gm)													
Mean	121.3	131.2	105.0	126.7	126.9	102.2	126.3	120.3	163.5	124.8	126.3		
Std. Dev.	16.7	20.9	19.1	14.1	32.5	7.5	21.0	24.0	20.5		20.5		
Variance	277.4	437.7	365.4	199.9	1054.3	56.2	441.3	577.5	418.8		418.8	9.2	se
Range	38.0	52.2	53.3	35.5	82.0	14.6	57.5	60.5	53.3		53.3	36.0	df
n	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0		5.0	2.339061	tcritical
												21.57494	dmin
C Peak Load (gm)												10.78747	bwidth
Mean	133.4	141.6	127.3	134.0	134.9	98.0	132.6	140.9	155.5	132.1	134.0		
Std. Dev.	13.1	12.0	28.0	40.8	19.5	15.8	27.5	13.5	15.6		15.8		
Variance	172.9	145.1	783.9	1660.9	381.4	249.3	757.9	182.1	244.2		249.3	10.1	se
Range	25.7	28.1	60.4	82.3	47.1	38.0	62.9	30.8	35.5		38.0	36.0	df
n	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0		5.0	2.339061	tcritical
												23.59155	dmin
N Area												11.79578	bwidth
Mean	779.9	876.4	627.5	783.6	795.0	727.1	782.9	770.0	1017.3	795.5	782.9		
Std. Dev.	147.5	162.8	99.1	63.0	165.8	69.7	138.6	147.0	81.3		138.6		
Variance	21766.1	26497.7	9820.6	3969.7	27492.0	4858.3	19221.3	21612.4	6611.4		19221.3	56.1	se
Range	367.6	425.3	205.3	154.8	435.8	174.8	338.5	379.0	189.2		338.5	36.0	df
n	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0		5.0	2.339061	tcritical
												131.3255	dmin
C Area												65.66277	bwidth
Mean	1031.6	1113.2	1048.8	1071.6	1118.6	933.3	1086.6	1047.2	1195.5	1065.5	1071.6		
Std. Dev.	139.3	63.2	219.7	135.5	103.9	109.3	77.1	147.4	171.9		135.5		
Variance	19401.0	3996.8	48259.0	18372.1	10794.1	11955.3	5941.1	21720.3	29556.0		18372.1	61.5	se
Range	324.8	156.0	577.9	356.2	263.0	296.0	213.0	360.3	406.4		324.8	36.0	df
n	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0		5.0	2.339061	tcritical
												143.7653	dmin
												71.88265	bwidth

Table 19: Tabulated Data for Matrix-Fabric B

Test Statistic	Fabric B												
	B1	B2	B3	B4	B5	B6	B7	B8		B All Styles	B Median		
Wt. (g/m^2)	170	176.25	173.75	176.25	172.5	171.25	170	173.75		173.0	173.1		
# Styles										8	8		
FAST-3													
E5-1 (%) Mean	0.5	0.6	0.6	0.5	0.4	0.4	0.2	0.2		0.4	0.5		
Std. Dev.	0.1	0.2	0.2	0.2	0.1	0.3	0.1	0.0			0.1		
Variance	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0			0.0	0.1	se
Range	0.2	0.3	0.4	0.3	0.2	0.5	0.1	0.0			0.3	16.0	df
n	3	3	3	3	3	3	3	3			3.0	2.472878	tcritical
												0.17631	dmin
												0.088155	bwidth
E5-2 (%) Mean	0.5	0.5	0.5	0.6	0.7	0.8	0.5	0.3		0.6	0.5		
Std. Dev.	0.1	0.1	0.2	0.0	0.4	0.2	0.1	0.1			0.1		
Variance	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0			0.0	0.1	se
Range	0.2	0.1	0.3	0.0	0.7	0.4	0.1	0.2			0.2	16.0	df
n	3	3	3	3	3	3	3	3			3.0	2.472878	tcritical
												0.190213	dmin
												0.095107	bwidth
E20-1 (%) Mean	1.2	1.8	1.5	1.5	1.1	1.1	0.8	0.7		1.2	1.2		
Std. Dev.	0.2	0.1	0.3	0.2	0.1	0.4	0.1	0.1			0.1		
Variance	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0			0.0	0.1	se
Range	0.3	0.2	0.6	0.3	0.1	0.7	0.1	0.1			0.3	16.0	df
n	3	3	3	3	3	3	3	3			3.0	2.472878	tcritical
												0.218865	dmin
												0.109432	bwidth
E20-2 (%) Mean	1.8	2.1	2.0	2.0	2.1	2.3	1.9	1.1		1.9	2.0		
Std. Dev.	0.2	0.2	0.2	0.1	0.3	0.3	0.1	0.1			0.2		
Variance	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0			0.0	0.1	se
Range	0.3	0.4	0.3	0.1	0.6	0.6	0.2	0.2			0.3	16.0	df
n	3	3	3	3	3	3	3	3			3.0	2.472878	tcritical
												0.217698	dmin
												0.108849	bwidth
E100-1 (%) Mean	2.8	4.9	3.7	4.3	3.3	2.5	2.0	2.3		3.2	3.1		
Std. Dev.	0.3	0.3	0.5	0.3	0.2	0.4	0.1	0.1			0.3		
Variance	0.1	0.1	0.2	0.1	0.0	0.2	0.0	0.0			0.1	0.1	se
Range	0.6	0.6	0.9	0.6	0.3	0.8	0.2	0.2			0.6	16.0	df
n	3	3	3	3	3	3	3	3			3.0	2.472878	tcritical
												0.330232	dmin
												0.165116	bwidth
E100-2 (%) Mean	5.5	5.9	6.3	6.1	6.5	6.0	5.4	4.2		5.7	6.0		
Std. Dev.	0.6	0.2	0.4	0.5	0.5	0.5	0.2	0.3			0.4		
Variance	0.4	0.0	0.1	0.3	0.2	0.2	0.0	0.1			0.2	0.2	se
Range	1.1	0.3	0.7	1.0	0.9	0.9	0.3	0.5			0.8	16.0	df
n	3	3	3	3	3	3	3	3			3.0	2.472878	tcritical
												0.460978	dmin
												0.230489	bwidth
EB5 (%) Mean	4.1	4.5	4.1	4.6	3.9	3.9	3.8	2.5		3.9	4.0		
Std. Dev.	0.3	0.2	0.5	0.3	0.3	0.3	0.2	0.3			0.3		
Variance	0.1	0.0	0.3	0.1	0.1	0.1	0.0	0.1			0.1	0.1	se
Range	0.7	0.5	1.5	0.8	0.8	0.8	0.4	0.7			0.8	40.0	df
n	6	6	6	6	6	6	6	6			6.0	2.328935	tcritical
												0.333182	dmin
												0.166591	bwidth
RPT Procedure													
Ring Diameter (cm)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5		2.5	2.5		
Mounting Req. (Y/N)	X	X	X	X	X	X	X	X		X	X		
Crosshead Req. (Y/N)	N	N	N	N	N	N	N	N		N	N		
RPT Output													
N Peak Load (gm)													
Mean	101.9	90.6	82.9	104.6	82.7	99.4	144.6	105.8		101.6	100.7		
Std. Dev.	12.4	21.7	9.5	24.1	11.4	22.2	41.2	20.1		27.6	20.9		
Variance	154.5	471.2	90.7	581.9	129.1	490.6	1694.8	403.6				10.0	se
Range	29.4	47.4	21.4	58.0	28.2	61.9	109.0	49.2		142.3	48.3	32.0	df
n	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0				2.351835	tcritical
												23.56699	dmin
C Peak Load (gm)												11.7835	bwidth
Mean	109.2	97.7	107.4	95.8	98.4	101.2	125.5	133.8		108.6	104.3		
Std. Dev.	12.6	28.2	19.2	15.6	25.9	17.7	15.1	26.2		23.0	18.5		
Variance	158.3	793.8	369.4	242.5	669.9	313.2	227.3	686.7				9.3	se
Range	32.0	66.6	52.2	37.9	64.2	46.1	40.3	67.5		119.5	49.2	32.0	df
n	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0				2.351835	tcritical
												21.8768	dmin
N Area												10.9384	bwidth
Mean	675.8	597.1	583.1	593.6	500.7	602.7	799.9	670.6		627.9	599.9		
Std. Dev.	103.2	126.6	47.4	85.1	39.6	149.5	170.0	93.4		130.5	98.3		
Variance	10653.3	16030.0	2248.1	7236.4	1571.9	22341.7	28887.9	8726.1				49.4	se
Range	261.5	297.1	97.5	184.4	101.0	359.7	437.0	255.9		677.6	258.7	32.0	df
n	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0				2.351835	tcritical
												116.2288	dmin
C Area												58.11438	bwidth
Mean	937.2	815.5	859.6	786.4	699.1	832.6	948.6	1033.1		864.0	846.1		
Std. Dev.	145.7	110.2	97.7	66.7	154.2	88.2	199.3	195.1		161.4	128.0		
Variance	21223.7	12148.9	9551.3	4444.4	23786.9	7787.6	39717.6	38062.7				62.6	se
Range	352.1	263.3	228.2	168.0	417.8	225.3	501.6	477.1		889.1	307.7	32.0	df
n	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0				2.351835	tcritical
												147.212	dmin
												73.60602	bwidth

The following are the equations for the additional parameters that were calculated to form the framework of the matrix (22):

SAMPLE STANDARD DEVIATION $s_p = \sqrt{(s_1^2 + s_2^2) \div 2}$

STANDARD ERROR $s_e = s_p \div \sqrt{n}$

Where:

- ***n*** is the sample size, or number of replicates

DEGREES OF FREEDOM $df = n * N - N$

Where:

- ***N*** is the number of styles within a fabric type

t CRITICAL $tcritical = (df, \alpha)$

Where:

- ***α*** is based on a two-tailed test with a 95% confidence interval, with α = 0.025

d STATISTIC $d\min = tcritical * se$

BIN WIDTH $bwidth = d\min \div 2$

The tabulated values from the tables for fabrics A and B were then used to develop visualization charts for each fabric type that serve as the matrix.

Table 20: Comfort Measurement Matrix (Blank)-Fabric A

FAST-3 OUTPUT-FABRIC A																					
E5-1 (%) Mean	<		0.0		0.1		0.4		0.6		0.8		1.0		1.2		1.5		1.7		<
E5-2 (%) Mean	<		0.0		0.2		0.5		0.8		1.1		1.4		1.7		2.0		2.2		<
E20-1 (%) Mean	<		0.4		0.7		1.1		1.4		1.7		2.0		2.3		2.6		2.9		<
E20-2 (%) Mean	<		0.9		1.4		1.9		2.4		2.9		3.2		3.5		3.9		4.2		<
E100-1 (%) Mean	<		2.4		2.8		3.1		3.5		3.9		4.4		4.9		5.4		5.9		<
E100-2 (%) Mean	<		6.6		6.9		7.1		7.4		7.7		8.0		8.3		8.5		8.8		<
EB5 (%) Mean	<		4.3		4.6		4.8		5.1		5.4		5.7		6.0		6.2		6.5		<
RPT OUTPUT-FABRIC A																					
N Peak Load (gm)	>		167.9		157.2		146.4		135.6		124.8		114.0		103.2		92.4		81.7		>
C Peak Load (gm)	>		179.3		167.5		155.7		143.9		132.1		120.3		108.5		96.7		84.9		>
N Area (gm*cm)	>		1058.2		992.5		926.8		861.2		795.5		729.8		664.2		598.5		532.8		>
C Area (gm*cm)	>		1353.0		1281.1		1209.3		1137.4		1065.5		993.6		921.7		849.9		778.0		>
		1		2		3		4		5		6		7		8		9		10	

<<<----- REDUCED COMFORT	MEAN	IMPROVED COMFORT ----->>>

Table 21: Comfort Measurement Matrix (Blank)-Fabric B

FAST-3 OUTPUT-FABRIC B																					
E5-1 (%) Mean	<		0.0		0.1		0.2		0.3		0.4		0.5		0.6		0.7		0.8		<
E5-2 (%) Mean	<		0.2		0.3		0.4		0.5		0.6		0.7		0.8		0.9		1.0		<
E20-1 (%) Mean	<		0.8		0.9		1.0		1.1		1.2		1.3		1.4		1.5		1.6		<
E20-2 (%) Mean	<		1.2		1.4		1.6		1.7		1.9		2.0		2.1		2.2		2.3		<
E100-1 (%) Mean	<		2.3		2.5		2.7		3.0		3.2		3.4		3.5		3.7		3.9		<
E100-2 (%) Mean	<		5.0		5.2		5.4		5.5		5.7		5.9		6.0		6.2		6.4		<
EB5 (%) Mean	<		3.2		3.4		3.6		3.7		3.9		4.1		4.2		4.4		4.6		<
RPT OUTPUT-FABRIC B																					
N Peak Load (gm)	>		148.7		137.0		125.2		113.4		101.6		89.8		78.0		66.2		54.5		>
C Peak Load (gm)	>		152.4		141.4		130.5		119.5		108.6		97.7		86.7		75.8		64.8		>
N Area (gm*cm)	>		860.4		802.3		744.2		686.0		627.9		569.8		511.7		453.6		395.5		>
C Area (gm*cm)	>		1158.4		1084.8		1011.2		937.6		864.0		790.4		716.8		643.2		569.6		>
		1		2		3		4		5		6		7		8		9		10	

<<<----- REDUCED COMFORT	MEAN	IMPROVED COMFORT ----->>>

The matrix allows for the visual ordering of fabric styles along multiple test parameters at the same time. The y-axis is composed of objective test parameters, with FAST-3 extension values shown above and RPT parameters shown below. Along the x-axis are ten bins, in which styles are placed, based on their mean values for each parameter. The bins are centered on the mean values for the entire fabric type. Each bin consists of a range of values based on the bwidth values derived from the tabulated data tables. For instance Bin 6 consists of the range of values = type mean ≤ (type mean + 1(bwidth). Bin 7 consists of the range of values = type mean + 1(bwidth) ≤ type mean + 2(bwidth).

The dmin values for a particular parameter are based on the idea that if two fabric styles have different values for a test parameter, the dmin is the smallest difference between these two numbers that makes them different at a 95%

confidence interval. Since the bwidth values are half of the dmin values, it cannot be stated that styles that fall in Bin 6 are statistically different than those in Bin 7, but it is safe to say that there is a statistical difference between Bin 6 styles and those in Bin 9. With that stated, Table 22 is the Comfort Measurement Matrix for fabric A, with all styles being assigned bins based on the mean values for those styles.

Table 22: Comfort Measurement Matrix (Filled)-Fabric A

FAST-3 OUTPUT-FABRIC A																					
E5-1 (%) Mean	<		0.0		0.1		0.4	A3 A7	0.6	A5 A9	0.8	A1 A2 A8	1.0	A6	1.2	A4	1.5		1.7		<
E5-2 (%) Mean	<		0.0		0.2		0.5		0.8	A2 A4 A5 A6 A7 A9	1.1	A1	1.4	A3 A8	1.7		2.0		2.2		<
E20-1 (%) Mean	<		0.4		0.7	A3	1.1	A7	1.4	A1 A9	1.7	A5 A8	2.0	A2 A6	2.3	A4	2.6		2.9		<
E20-2 (%) Mean	<		0.9		1.4		1.9		2.4	A2 A4 A5 A6 A7 A9	2.9		3.2	A1	3.5	A3 A8	3.9		4.2		<
E100-1 (%) Mean	<	A3	2.4		2.8	A1 A7	3.1		3.5	A8 A9	3.9		4.4	A5 A6	4.9	A2 A4	5.4		5.9		<
E100-2 (%) Mean	<		6.6		6.9	A9	7.1	A2 A6	7.4	A4 A5 A7	7.7	A1	8.0		8.3	A8	8.5		8.8	A3	<
EB5 (%) Mean	<		4.3	A9	4.6		4.8	A4	5.1	A8	5.4	A1 A3 A5 A6	5.7	A7	6.0	A2	6.2		6.5		<
RPT OUTPUT-FABRIC A																					
N Peak Load (gm)	>		167.9	A9	157.2		146.4		135.6	A2 A4 A5 A7	124.8	A1 A8	114.0	A3	103.2	A6	92.4		81.7		>
C Peak Load (gm)	>		179.3		167.5		155.7	A9	143.9	A1 A2 A4 A5 A7 A8	132.1	A3	120.3		108.5	A6	96.7		84.9		>
N Area (gm*cm)	>		1058.2	A9	992.5		926.8	A2	861.2		795.5	A1 A4 A5 A7 A8	729.8	A6	664.2	A3	598.5		532.8		>
C Area (gm*cm)	>		1353.0		1281.1		1209.3	A9	1137.4	A2 A4 A5 A7	1065.5	A1 A3 A8	993.6	A6	921.7		849.9		778.0		>
		1		2		3		4		5		6		7		8		9		10	

<<<----- REDUCED COMFORT | MEAN | IMPROVED COMFORT ----->>>

Table 23: Comfort Measurement Matrix (Filled)-Fabric B

FAST-3 OUTPUT-FABRIC B																					
E5-1 (%) Mean	<		0.0		0.1		0.2	B7 B8	0.3		0.4	B5 B6	0.5	B1 B4	0.6	B2 B3	0.7		0.8		<
E5-2 (%) Mean	<		0.2		0.3	B8	0.4		0.5	B1 B2 B3 B7	0.6	B4	0.7	B5	0.8	B6	0.9		1.0		<
E20-1 (%) Mean	<	B8	0.8	B7	0.9		1.0		1.1	B5 B6	1.2	B1	1.3		1.4		1.5	B3 B4	1.6	B2	<
E20-2 (%) Mean	<	B8	1.2		1.4		1.6		1.7	B1	1.9	B7	2.0	B3 B4	2.1	B2 B5	2.2		2.3	B6	<
E100-1 (%) Mean	<	B7	2.3	B8	2.5	B6	2.7	B1	3.0		3.2	B5	3.4		3.5		3.7	B3	3.9	B2 B4	<
E100-2 (%) Mean	<	B8	5.0		5.2		5.4	B7	5.5	B1	5.7		5.9	B2	6.0	B4 B6	6.2	B3	6.4	B5	<
EB5 (%) Mean	<	B8	3.2		3.4		3.6		3.7	B7	3.9	B5 B6	4.1	B1 B3	4.2		4.4	B2	4.6	B4	<
RPT OUTPUT-FABRIC B																					
N Peak Load (gm)	>		148.7	B7	137.0		125.2		113.4	B1 B4 B8	101.6	B2 B6	89.8	B3 B5	78.0		66.2		54.5		>
C Peak Load (gm)	>		152.4		141.4	B8	130.5	B7	119.5	B1	108.6	B3 B2 B5 B6	97.7	B4	86.7		75.8		64.8		>
N Area (gm*cm)	>		860.4		802.3	B7	744.2		686.0	B1 B8	627.9	B3 B2 B4 B6	569.8		511.7	B5	453.6		395.5		>
C Area (gm*cm)	>		1158.4		1084.8	B8	1011.2	B7	937.6	B1	864.0	B3 B2 B6	790.4	B4	716.8	B5	643.2		569.6		>
		1		2		3		4		5		6		7		8		9		10	

<<<----- REDUCED COMFORT | MEAN | IMPROVED COMFORT ----->>>

The matrices provide a more simplistic way of looking at the data, as compared to ANOVA plots for each parameter. At a glance, one can see that certain styles are behaving differently than other styles within their type. For fabrics A and B, the washable easy-care styles A9 and B8 are once again shown to have reduced comfort, with all values for these styles falling to the left of the mean across all test parameters. Style A3 shows some back-and-forth movement due to directional extension, though this softened style is shown to have improved comfort in many areas. The same is true of the other softened styles, A6 and B5. Depending on the end-use of a particular fabric type, warp, weft, or bias extension might be more desirable. The matrix thus allows the viewer to analyze areas of improved potential comfort for a fabric style. This is particularly evident with styles A2 and B2, the warp stretch-finished fabrics. A2 and B2 show improved comfort in warp directional extension versus weft directional extension. Therefore the matrix can help to categorize fabrics as being more or less comfortable based on a number of parameters simultaneously.

The matrix is a simple analysis tool that can be easily modified to adjust for changes in fabric types over time. Perhaps most importantly, though, the matrix can be updated with additional test parameters relating to properties of comfort that were not able to be tested in this research.

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APPENDICES

7 Appendix A

Table 24: Subjective Evaluation Rank Order Data-Fabric A

		Ranking (1 is best)					
Style	Respondent	End Use	Comfort	Compression	Extension	Bending	Surface
A1	AW	7	7	5	9	5	6
A2	AW	1	1	1	3	6	7
A3	AW	4	4	2	4	1	3
A4	AW	5	5	3	5	7	8
A5	AW	6	6	6	7	2	2
A6	AW	2	2	10	6	3	1
A7	AW	3	3	4	10	9	9
A8	AW	8	8	7	8	4	4
A9	AW	9	9	8	2	10	5
D1C	AW	10	10	9	1	8	10
A1	NA	2	2	2	2	3	9
A2	NA	3	3	3	6	5	2
A3	NA	5	5	5	3	2	3
A4	NA	6	6	8	5	4	4
A5	NA	1	1	6	8	1	1
A6	NA	4	4	7	10	6	5
A7	NA	9	9	4	4	9	10
A8	NA	8	8	10	7	7	8
A9	NA	10	10	9	9	10	7
D1C	NA	7	7	1	1	8	6
A1	RM	8	8	5.5	8	5.5	5.5
A2	RM	4	4	5.5	4	5.5	5.5
A3	RM	3	3	5.5	9	5.5	5.5
A4	RM	5	5	5.5	3	5.5	5.5
A5	RM	1	1	5.5	1	5.5	5.5
A6	RM	2	2	5.5	5	5.5	5.5
A7	RM	6	6	5.5	7	5.5	5.5
A8	RM	10	10	5.5	10	5.5	5.5
A9	RM	7	7	5.5	6	5.5	5.5
D1C	RM	9	9	5.5	2	5.5	5.5
A1	DB	6	6	6	6	1	6
A2	DB	1	1	6	2	6	6
A3	DB	6	6	6	6	6	6
A4	DB	6	6	6	6	6	6
A5	DB	6	6	6	6	6	1
A6	DB	6	6	6	6	6	6
A7	DB	6	6	6	6	6	6
A8	DB	6	6	6	6	6	6
A9	DB	6	6	6	6	6	6
D1C	DB	6	6	1	1	6	6
A1	CL	3	3	9	9	2	5
A2	CL	6	6	10	4	3	3
A3	CL	4	4	5	9	9	2
A4	CL	5	5	6	5	1	1
A5	CL	8	8	7	3	4	7
A6	CL	1	1	2	6	5	4
A7	CL	7	7	3	1	8	9
A8	CL	2	2	1	9	7	7
A9	CL	9	9	4	7	6	7
D1C	CL	10	10	8	2	10	10
A1	ST	9	9	5.5	5	5.5	5
A2	ST	3	3	5.5	5	5.5	5
A3	ST	10	10	5.5	5	5.5	5
A4	ST	6	6	5.5	5	5.5	5
A5	ST	1	1	5.5	5	5.5	5
A6	ST	3	3	5.5	5	1	5
A7	ST	5	5	5.5	5	5.5	5
A8	ST	3	3	5.5	10	5.5	5
A9	ST	7	7	5.5	5	5.5	5
D1C	ST	8	8	5.5	5	10	10

Table 25: Subjective Evaluation Rank Order Data-Fabric B

		Ranking (1 is best)					
Style	**Respondent**	**End Use**	**Comfort**	**Compression**	**Extension**	**Bending**	**Surface**
B1	CE	7	7	6	5	5	9
B2	CE	1	1	2	1	2	2
B3	CE	6	6	1	8	4	4
B4	CE	2	2	3	2	1	1
B5	CE	9	9	5	4	7	3
B6	CE	5	5	8	6	8	7
B7	CE	4	4	4	7	3	6
B8	CE	8	8	9	9	9	5
D1C	CE	3	3	7	3	6	8
B1	AS	7	7	6	7	2	5
B2	AS	2	3	4	8	8	4
B3	AS	1	2	2	5	3	2
B4	AS	5	4	5	3	4	3
B5	AS	8	1	1	2	1	1
B6	AS	3	6	7	9	7	7
B7	AS	4	5	3	4	6	6
B8	AS	6	8	8	6	5	8
D1C	AS	10	10	9	1	9	9
B1	SJ	4	4	8	7	5	2
B2	SJ	1	1	5	9	8	8
B3	SJ	6	6	1	6	7	7
B4	SJ	5	5	9	2	3	1
B5	SJ	8	8	6	4	1	3
B6	SJ	3	3	3	1	6	9
B7	SJ	7	7	2	8	2	4
B8	SJ	9	9	4	5	4	6
D1C	SJ	2	2	7	3	9	5
B1	RM	1	8	6.5	7	5	7
B2	RM	9	1	6.5	1	5	2
B3	RM	5	9	6.5	7	5	7
B4	RM	4	5	1	4	5	7
B5	RM	8	2	6.5	2	5	3
B6	RM	3	6	6.5	7	5	7
B7	RM	2	7	6.5	7	5	7
B8	RM	6	4	3	7	5	1
D1C	RM	7	3	2	3	5	4
B1	DB	5	6	5	5.5	5	5
B2	DB	5	6	5	5.5	5	1
B3	DB	5	6	5	5.5	5	2
B4	DB	5	1	5	5.5	5	9
B5	DB	5	6	5	5.5	5	6
B6	DB	5	6	5	5.5	5	4
B7	DB	5	6	5	5.5	5	7
B8	DB	5	6	5	5.5	5	8
D1C	DB	5	2	5	1	5	3
B1	NA	5	5	4	9	4	6
B2	NA	1	1	1	4	2	4
B3	NA	3	3	8	2	5	2
B4	NA	7	7	2	3	6	7
B5	NA	2	2	7	5	1	1
B6	NA	8	8	3	7	8	3
B7	NA	4	4	6	8	3	5
B8	NA	6	6	5	6	7	8
D1C	NA	9	9	9	1	9	9

Table 26: Subjective Evaluation Rank Order Data-Fabric C

		Ranking (1 is best)					
Style	Respondent	End Use	Comfort	Compression	Extension	Bending	Surface
C1	CE	1	2	2	2	2	1
C2	CE	2	3	4	4	4	2
C3	CE	5	5	5	5	5	5
D1C	CE	3	1	1	1	1	3
C1	NA	2	2	2	2	2	2
C2	NA	3	3	3	3	3	3
C3	NA	5	5	5	4	4	5
D1C	NA	1	1	1	1	1	1
C1	RA	2	2	4	3	2	2
C2	RA	3	3	2	4	3	3
C3	RA	5	5	5	5	5	4
D1C	RA	1	1	1	1	1	1
C1	RM	1	2	2	4	2	2
C2	RM	3	3	4	5	3	5
C3	RM	5	4	5	3	5	4
D1C	RM	2	1	1	1	1	1
C1	DB	2	2	2	3	2	2
C2	DB	3	5	4	5	4	5
C3	DB	5	4	5	4	5	4
D1C	DB	1	1	1	1	1	1
C1	MD	4	2	4	2	2	2
C2	MD	1	1	3	4	5	4
C3	MD	2	4	5	5	3	5
D1C	MD	5	5	1	1	1	1

Table 27: Subjective Evaluation Rank Order Data-Fabric D

		Ranking (1 is best)					
Style	**Respondent**	**End Use**	**Comfort**	**Compression**	**Extension**	**Bending**	**Surface**
D1	SJ	1	1	1	4	1	3
D2	SJ	4	4	3	1	4	4
D3	SJ	3	3	4	2	3	2
D1C	SJ	2	2	2	3	2	1
D1	AW	1	1	1	1	1	1
D2	AW	4	4	4	3	4	4
D3	AW	3	3	3	4	3	3
D1C	AW	2	2	2	2	2	2
D1	RDM	3	1	4	1	1	2
D2	RDM	1	4	1	2	4	4
D3	RDM	2	3	2	3	3	3
D1C	RDM	4	2	3	2	2	1
D1	EH	1	1	4	2	2	1
D2	EH	3	2	3	3	3	4
D3	EH	4	3	2	4	4	3
D1C	EH	2	4	5	1	1	2
D1	MB	4	1	3	4	1	2
D2	MB	1	4	2	2	4	4
D3	MB	2	3	1	3	3	3
D1C	MB	3	2	4	1	2	1
D1	DB	2	2	2	3	2	2
D2	DB	3	5	4	5	4	5
D3	DB	4	4	5	4	3	3
D1C	DB	1	1	1	1	1	1

Table 28: Subjective Evaluation Rank Order Data-Fabric E

		Ranking (1 is best)					
Style	**Respondent**	**End Use**	**Comfort**	**Compression**	**Extension**	**Bending**	**Surface**
E1	CE	4	4	3	2	3	4
E2	CE	2	2	1	3	4	1
D1C	CE	1	1	2	1	1	2
E1	KG	4	4	3	2	3	4
E2	KG	1	2	2	3	4	3
D1C	KG	2	1	1	1	1	1
E1	MJK	3	3	3	2	4	4
E2	MJK	1	1	1	3	3	2
	MJK	2	2	2	1	1	1
E1	SJ	4	4	4	2	4	4
E2	SJ	1	2	3	3	3	2
D1C	SJ	3	1	2	1	1	1
E1	DB	4	4	4	2	3	4
E2	DB	1	2	2	4	4	3
D1C	DB	3	1	1	1	1	1
E1	MD	3	4	4	2	3	3
E2	MD	4	3	1	4	4	4
D1C	MD	2	1	2	1	1	1

Table 29: Subjective Evaluation Rank Order Data-Fabric F

		Ranking (1 is best)					
Style	**Respondent**	**End Use**	**Comfort**	**Compression**	**Extension**	**Bending**	**Surface**
F1	CE	5	5	4	2	4	1
F2	CE	4	4	2	5	1	5
F3	CE	1	1	3	3	2	2
F4	CE	6	6	5	6	3	4
D1C	CE	2	2	6	4	6	3
F1	KG	1	3	4	6	4	6
F2	KG	3	5	6	2	5	5
F3	KG	4	6	3	4	6	3
F4	KG	2	4	2	3	3	4
D1C	KG	6	1	1	1	1	1
F1	SJ	4	4	4	6	3	5
F2	SJ	3	3	2	3	4	6
F3	SJ	2	2	1	4	5	4
F4	SJ	1	1	3	1	6	2
D1C	SJ	5	5	5	2	1	1
F1	DB	4	6	2	5	6	6
F2	DB	1	3	3	3	5	4
F3	DB	2	5	4	4	4	3
F4	DB	3	4	1	1	3	5
D1C	DB	6	1	6	2	1	1
F1	RA	5.5	4	5	6	5.5	6
F2	RA	2.5	5	3	4	3.5	3
F3	RA	5.5	6	6	3	5.5	5
F4	RA	2.5	2	4	1	3.5	4
D1C	RA	4	1	1	2	1	1
F1	MD	6	6	6	6	4	6
F2	MD	3	4	3.5	3	5	4
F3	MD	5	5	3.5	4	6	5
F4	MD	1	1	5	1	3	3
D1C	MD	4	2	1	2	1	2

Table 30: Fabric A FAST Mean Results

TEST	UNITS	Fabric A								
Dimension Stability		**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**A9**
RS-1	(%)	1.4	1.0	2.1	1.9	1.8	2.4	1.1	1.8	1.0
RS-2	(%)	0.2	-0.1	0.3	0.2	-0.2	0.3	0.6	0.5	0.3
HE-1	(%)	3.4	4.9	3.4	4.3	5.0	4.7	3.6	4.3	2.7
HE-2	(%)	4.8	4.6	5.9	4.7	5.0	5.0	4.7	4.9	4.1
Extension										
E5-1	(%)	0.9	0.8	0.4	1.4	0.7	1.0	0.5	0.9	0.7
E5-2	(%)	1.2	1.0	1.4	1.0	1.0	0.9	0.8	1.5	1.0
E20-1	(%)	1.6	2.1	0.9	2.5	1.8	2.0	1.1	1.7	1.5
E20-2	(%)	3.2	2.8	3.6	2.7	2.8	2.5	2.6	3.5	2.5
E100-1	(%)	2.9	5.2	2.3	5.1	4.6	4.6	2.8	3.8	3.7
E100-2	(%)	7.9	7.3	9.4	7.5	7.6	7.3	7.4	8.4	6.9
EB5	(%)	5.4	6.1	5.5	4.9	5.6	5.5	5.8	5.1	4.5
Bending										
C-1	(mm)	30.2	18.6	24.6	21.3	29.2	38.2	44.8	36.4	35.8
C-2	(mm)	9.8	25.4	22.1	21.3	19.0	29.7	37.8	26.7	41.6
B-1	(μN.m)	47.5	11.6	25.8	16.7	44.5	96.4	154.3	81.8	82.1
B-2	(μN.m)	1.6	29.2	18.7	16.8	12.3	45.3	92.7	32.4	128.4
Shear										
G	(N/m)	23.0	20.0	22.0	25.0	22.0	23.0	21.0	24.0	28.0
Formability										
F-1	(mm^2)	2.3	1.0	0.9	1.3	3.3	6.6	6.3	4.5	4.3
F-2	(mm^2)	0.2	3.5	2.7	2.0	1.5	5.0	11.4	4.3	13.1
Compression										
T2	(mm)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
T100	(mm)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
ST	(mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T2R	(mm)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
T100R	(mm)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
STR	(mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
W	(g/m^2)	175.0	182.0	177.0	177.0	182.0	177.0	175.0	172.0	182.0

Table 31: Fabric B FAST Mean Results

TEST	UNITS	Fabric B							
Dimension Stability		**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**
RS-1	(%)	1.4	1.0	1.4	1.4	1.4	1.2	1.2	1.0
RS-2	(%)	0.6	0.8	0.4	0.8	0.1	0.6	0.4	1.0
HE-1	(%)	2.7	4.4	4.0	4.0	3.6	2.5	3.1	2.5
HE-2	(%)	3.5	4.5	4.5	4.3	3.7	3.9	3.5	3.5
Extension									
E5-1	(%)	0.5	0.6	0.6	0.5	0.4	0.4	0.2	0.2
E5-2	(%)	0.5	0.5	0.5	0.6	0.7	0.8	0.5	0.3
E20-1	(%)	1.2	1.8	1.5	1.5	1.1	1.1	0.8	0.7
E20-2	(%)	1.8	2.1	2.0	2.0	2.1	2.3	1.9	1.1
E100-1	(%)	2.8	4.9	3.7	4.3	3.3	2.5	2.0	2.3
E100-2	(%)	5.5	5.9	6.3	6.1	6.5	6.0	5.4	4.2
EB5	(%)	4.1	4.5	4.1	4.6	3.9	3.9	3.8	2.5
Bending									
C-1	(mm)	16.5	23.9	19.9	19.6	20.1	19.6	21.9	19.9
C-2	(mm)	12.6	22.4	20.5	21.8	21.7	20.4	20.9	20.8
B-1	(µN.m)	7.5	23.7	13.5	13.1	13.7	12.6	17.6	13.5
B-2	(µN.m)	3.3	19.3	14.7	17.9	17.4	14.2	15.3	15.4
Shear									
G	(N/m)	30.0	27.0	30.0	27.0	31.0	32.0	33.0	49.0
Formability									
F-1	(mm^2)	0.4	1.9	0.9	0.9	0.7	0.6	0.7	0.4
F-2	(mm^2)	0.3	2.1	1.4	1.8	1.7	1.5	1.5	0.9
Compression									
T2	(mm)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
T100	(mm)	2.2	2.2	2.2	2.3	2.2	2.2	2.2	2.2
ST	(mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T2R	(mm)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
T100R	(mm)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
STR	(mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
W	(g/m^2)	170.0	176.0	174.0	176.0	172.0	171.0	170.0	174.0

Table 32: Fabric C, D FAST Mean Results

TEST	UNITS	Fabric C			Fabric D		
Dimension Stability		**C1**	**C2**	**C3**	**D1**	**D2**	**D3**
RS-1	(%)	0.3	-0.1	0.8	0.4	1.1	0.3
RS-2	(%)	0.3	1.7	0.5	-6.8	0.3	-0.3
HE-1	(%)	3.0	2.6	3.1	6.2	4.3	2.9
HE-2	(%)	2.7	2.5	1.8	6.4	4.7	2.7
Extension							
E5-1	(%)	0.0	0.1	0.1	0.3	0.0	0.0
E5-2	(%)	0.0	0.1	0.1	2.1	0.8	0.8
E20-1	(%)	0.2	0.7	0.1	1.7	0.3	0.2
E20-2	(%)	0.5	0.0	0.0	9.7	4.0	3.0
E100-1	(%)	0.9	2.1	0.9	3.9	1.4	1.2
E100-2	(%)	2.5	0.6	0.4	18.3	12.1	10.2
EB5	(%)	0.8	0.5	1.0	3.6	1.3	1.9
Bending							
C-1	(mm)	31.9	30.7	31.5	23.9	29.7	29.5
C-2	(mm)	21.4	30.4	33.9	16.9	26.7	22.6
B-1	(μN.m)	50.0	45.1	48.0	20.5	37.4	36.5
B-2	(μN.m)	15.1	43.7	60.0	7.3	27.3	16.5
Shear							
G	(N/m)	154.0	224.0	117.0	34.0	93.0	63.0
Formability							
F-1	(mm^2)	0.5	2.1	0.1	1.9	0.9	0.6
F-2	(mm^2)	0.6	-0.3	-0.4	3.7	6.0	2.4
Compression							
T2	(mm)	2.2	2.2	2.2	2.2	2.2	2.2
T100	(mm)	2.2	2.2	2.2	2.2	2.2	2.2
ST	(mm)	0.0	0.0	0.0	0.0	0.0	0.0
T2R	(mm)	2.2	2.2	2.2	2.2	2.2	2.2
T100R	(mm)	2.2	2.2	2.2	2.2	2.2	2.2
STR	(mm)	0.0	0.0	0.0	0.0	0.0	0.0
W	(g/m^2)	157.0	158.0	157.0	152.0	146.0	145.0

Table 33: Fabric E, F FAST Mean Results

TEST	UNITS	Fabric E		Fabric F			
Dimension Stability		**E1**	**E2**	**F1**	**F2**	**F3**	**F4**
RS-1	(%)	0.3	-0.2	7.9	3.3	5.0	-4.3
RS-2	(%)	-0.4	0.2	2.5	-0.8	1.2	0.6
HE-1	(%)	1.2	-0.1	1.3	0.6	0.6	0.6
HE-2	(%)	-0.2	0.2	1.0	1.8	3.6	4.3
Extension							
E5-1	(%)	0.2	0.1	0.0	0.0	0.1	0.0
E5-2	(%)	0.1	0.0	0.1	0.0	0.0	0.0
E20-1	(%)	0.3	0.1	0.1	0.0	0.1	0.2
E20-2	(%)	0.4	0.0	0.0	0.4	0.1	0.5
E100-1	(%)	0.6	0.4	0.5	0.2	0.1	1.4
E100-2	(%)	2.4	0.6	0.8	3.1	2.1	4.6
EB5	(%)	0.2	0.5	0.0	0.0	0.0	0.1
Bending							
C-1	(mm)	40.4	53.8	47.7	65.7	73.6	44.2
C-2	(mm)	26.4	40.4	27.1	34.6	35.4	33.8
B-1	(μN.m)	129.0	309.2	324.1	933.2	1311.8	325.5
B-2	(μN.m)	36.2	130.6	59.2	136.3	146.6	145.0
Shear							
G	(N/m)	568.0	264.0	7307.0	3672.0	3672.0	2455.0
Formability							
F-1	(mm^2)	0.9	0.7	2.9	0.0	-3.0	3.7
F-2	(mm^2)	0.7	0.3	-0.1	3.7	1.3	5.3
Compression							
T2	(mm)	2.2	2.2	2.2	2.2	2.2	2.2
T100	(mm)	2.2	2.2	2.2	2.2	2.2	2.2
ST	(mm)	0.0	0.0	0.0	0.0	0.0	0.0
T2R	(mm)	2.2	2.2	2.2	2.2	2.2	2.2
T100R	(mm)	2.2	2.2	2.2	2.2	2.2	2.2
STR	(mm)	0.0	0.0	0.0	0.0	0.0	0.0
W	(g/m^2)	200.0	202.0	305.0	335.0	336.0	385.0

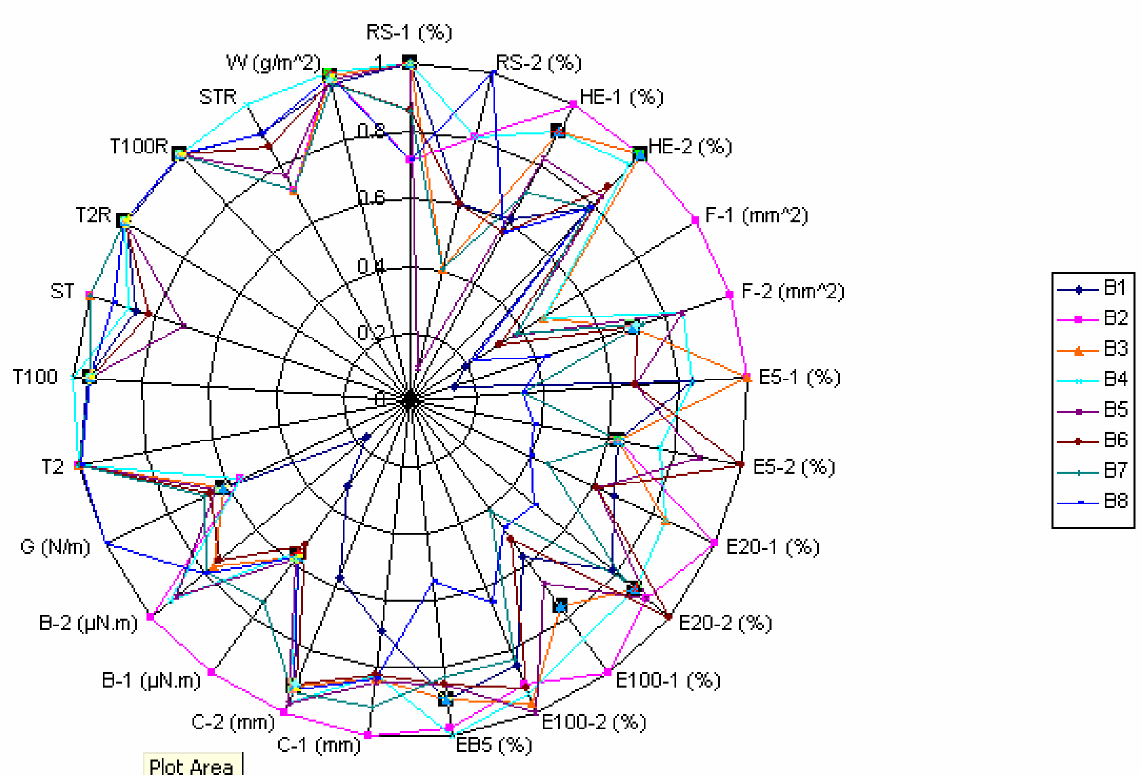


Figure 62: Radar Plot-Fabric B

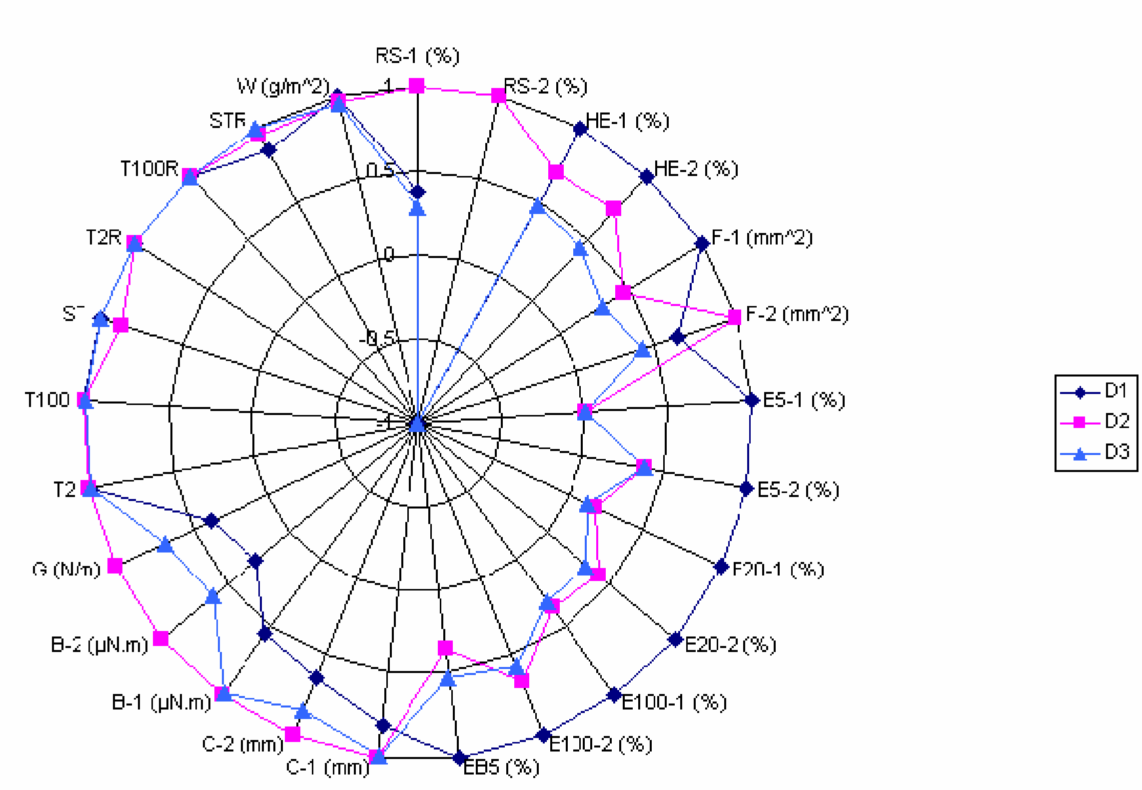


Figure 63: Radar Plot-Fabric D

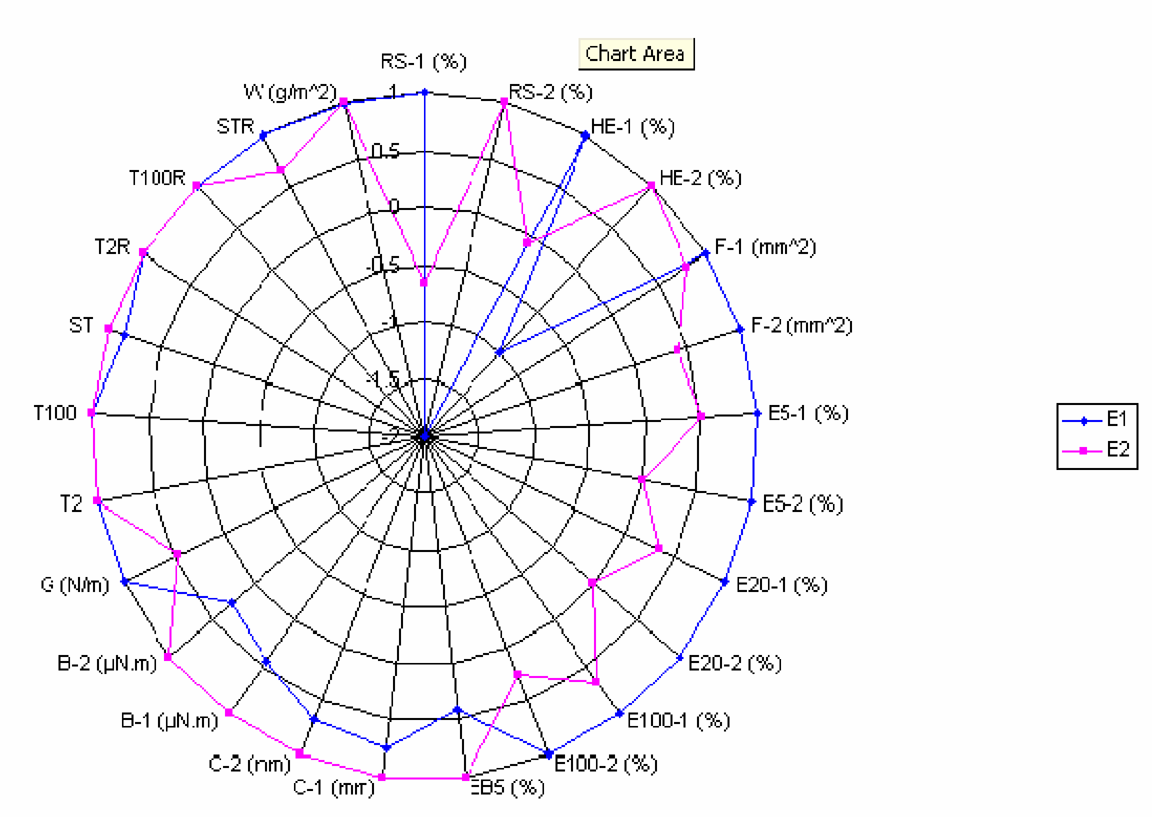
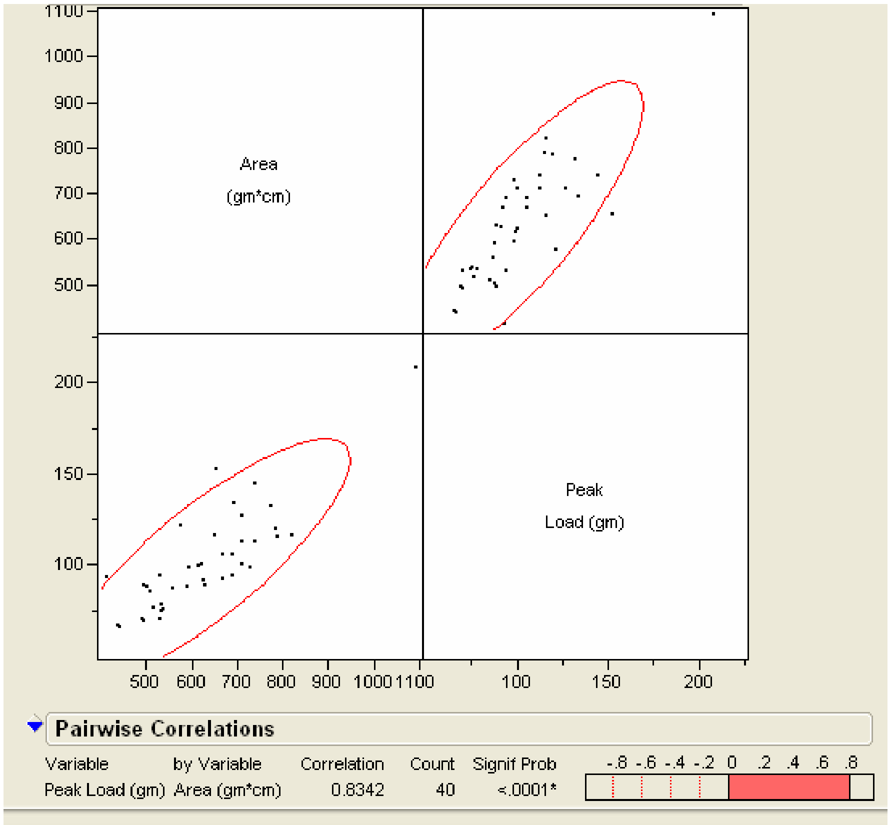


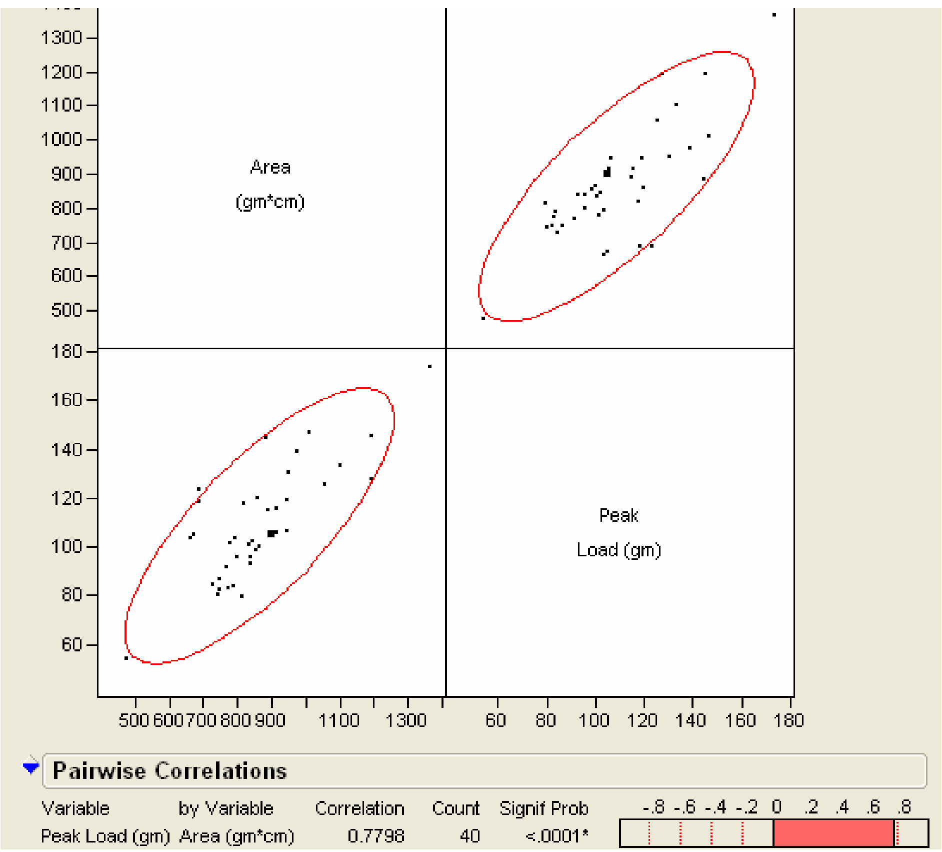
Figure 64: Radar Plot-Fabric E



Pairwise Correlations

Variable	by Variable	Correlation	Count	Signif Prob
Peak Load (gm)	Area (gm*cm)	0.8342	40	<.0001*

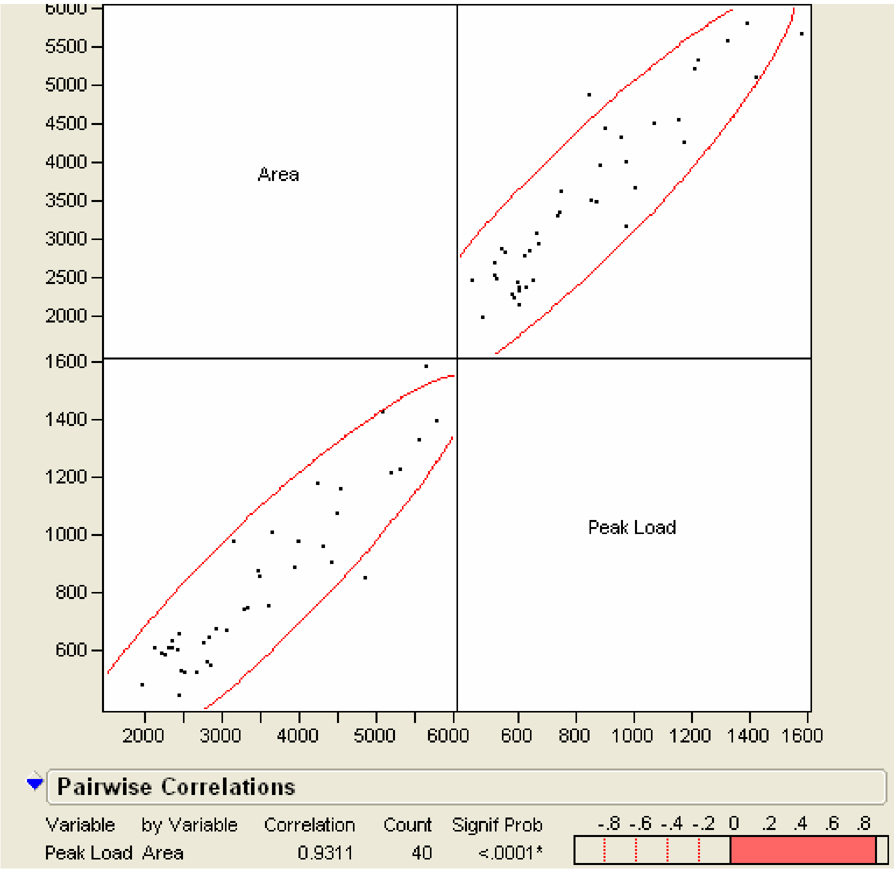
Figure 65: Fabric B Task 3 Pairwise of Area and Peak Load-Normal



Pairwise Correlations

Variable	by Variable	Correlation	Count	Signif Prob
Peak Load (gm)	Area (gm*cm)	0.7798	40	<.0001*

Figure 66: Fabric B Task 3 Pairwise of Area and Peak Load-Cylinder



Pairwise Correlations

Variable	by Variable	Correlation	Count	Signif Prob
Peak Load	Area	0.9311	40	<.0001*

Figure 67: Fabric F Task 3 Pairwise of Area and Peak Load

8 Appendix B

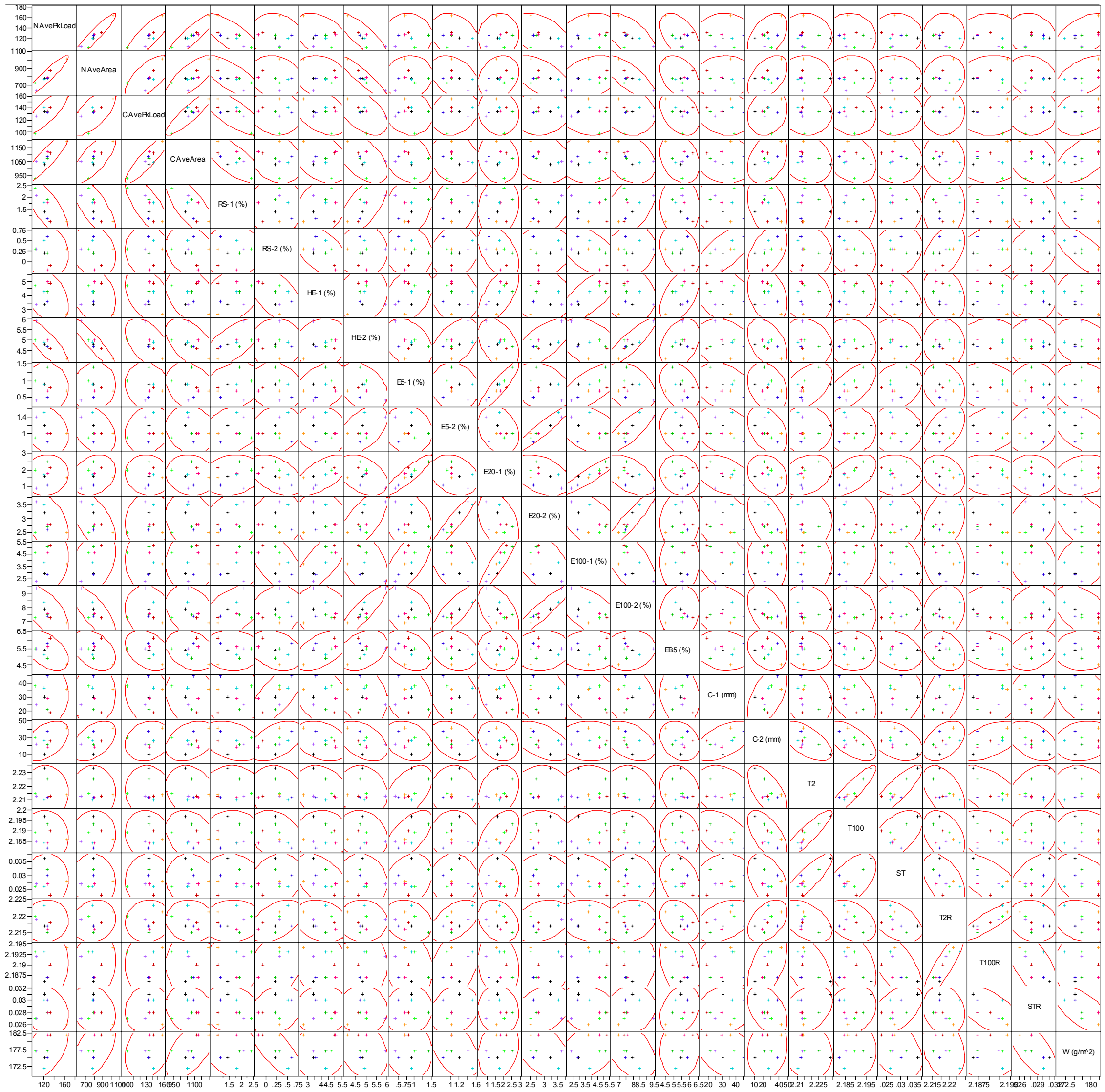


Figure 68: Fabric A Multivariate Scatterplot Matrix-FAST and RPT

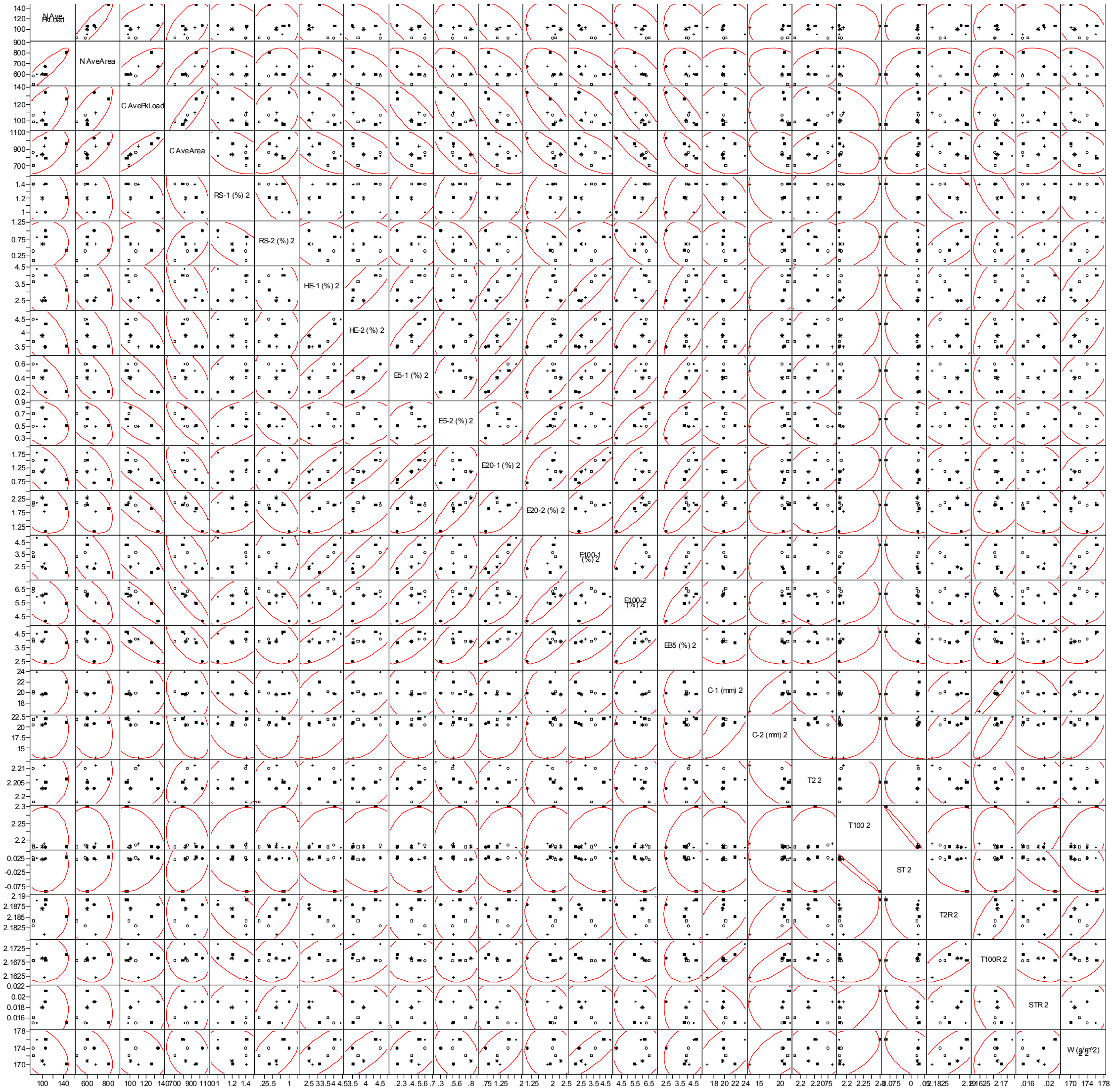


Figure 69: Fabric B Multivariate Scatterplot Matrix-FAST and RPT

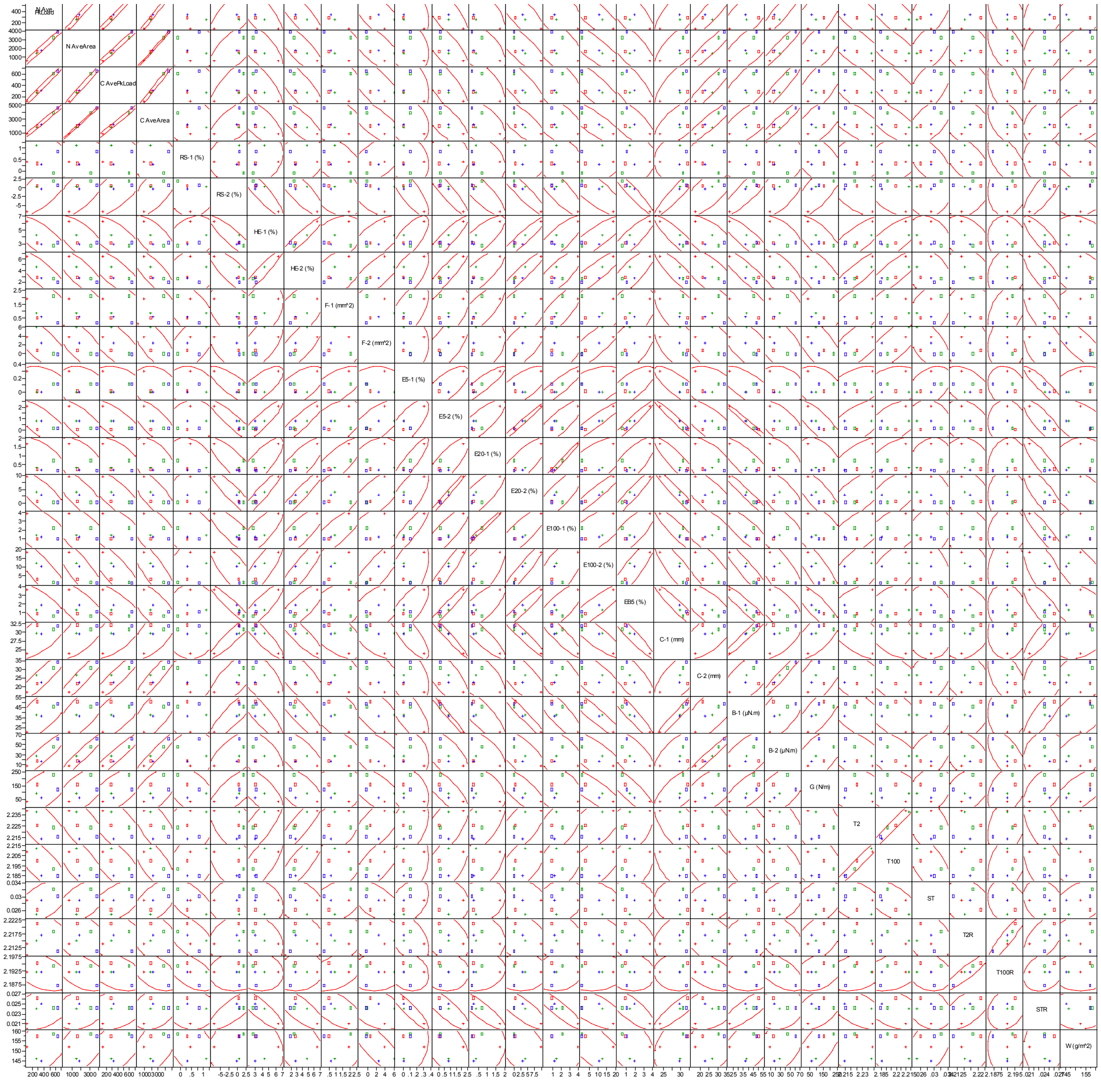


Figure 70: Fabric C, D Multivariate Scatterplot Matrix-FAST and RPT

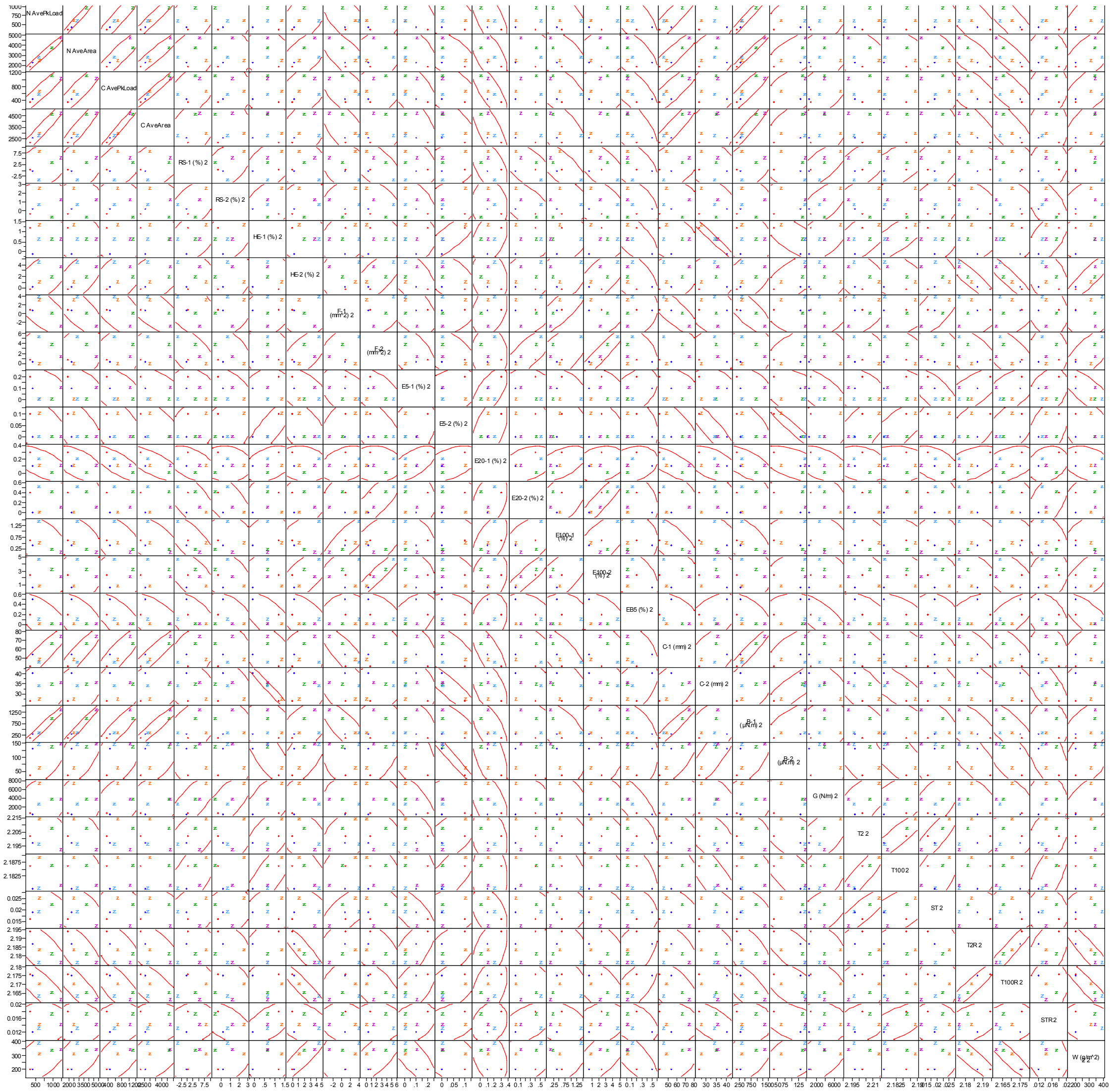


Figure 71: Fabric E, F Multivariate Scatterplot Matrix-FAST and RPT

9 Appendix C

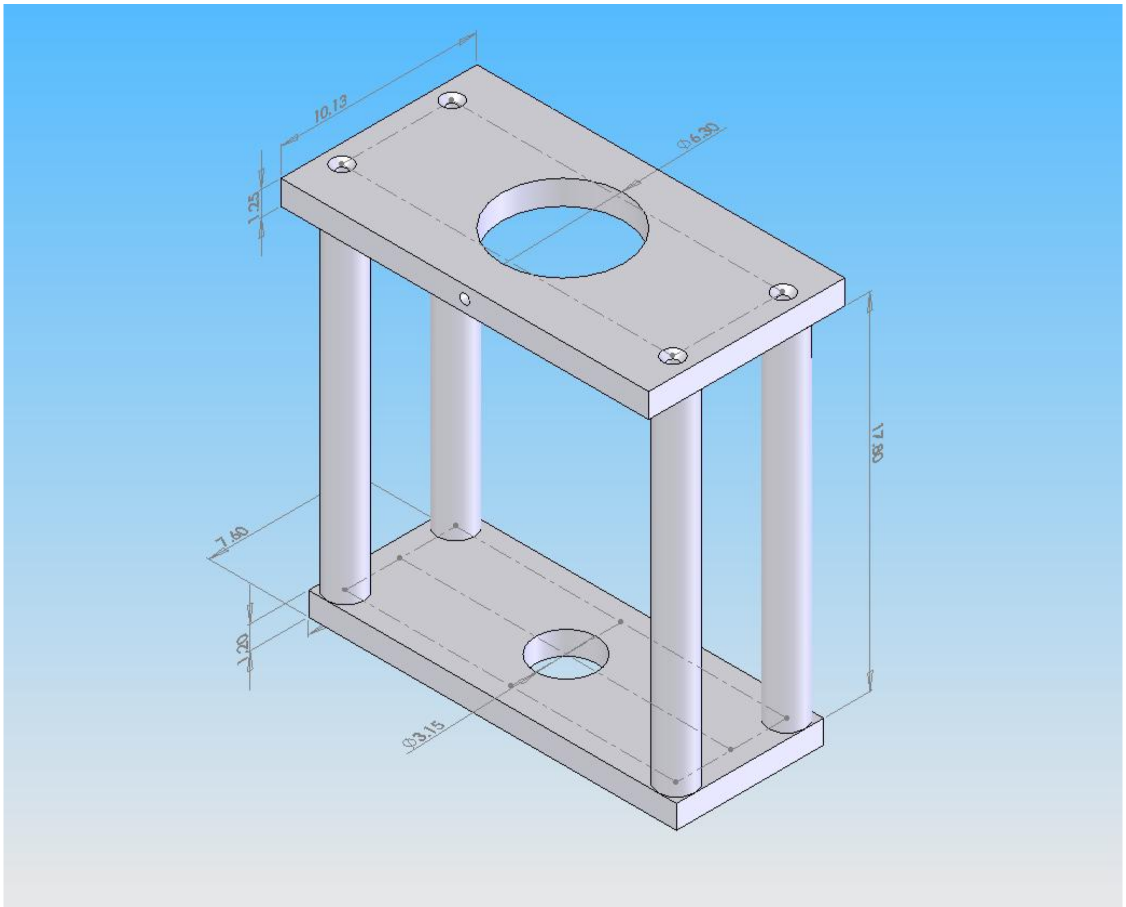


Figure 72: Ring Pull-Through Device Frame

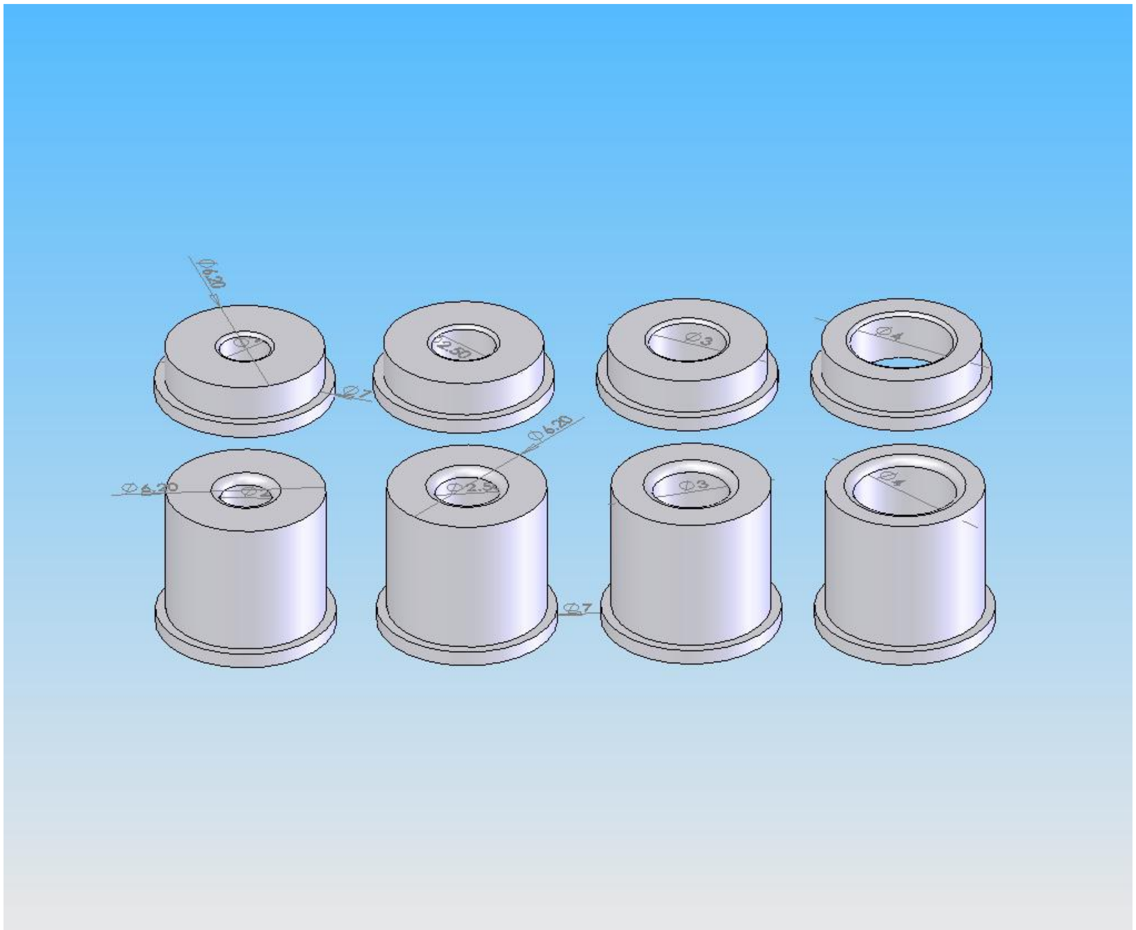


Figure 73: Ring Pull-Through Normal Rings and Cylinders

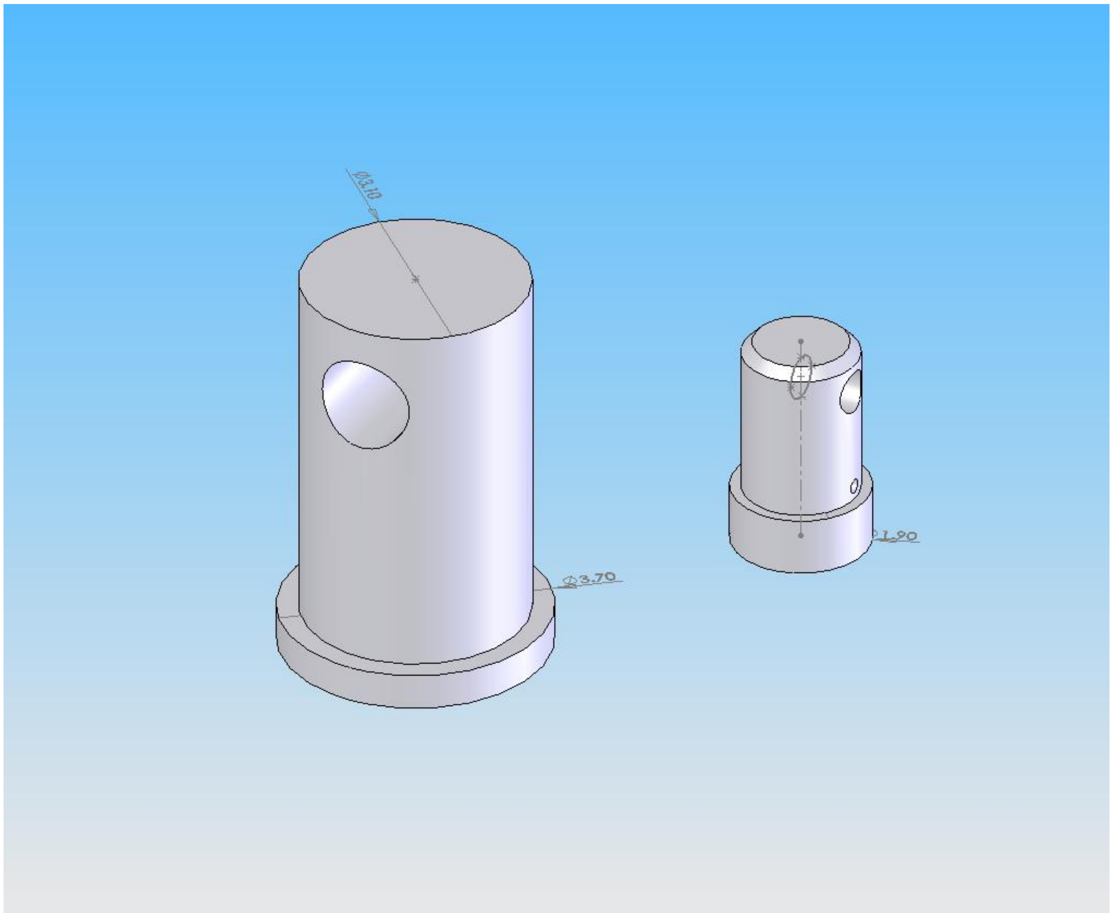


Figure 74: RPT Plug for Frame Base (left) and Mounting Pin Attachment