ABSTRACT

WATKINS, JESSICA LEIGH. Evaluation of Grip and Dexterity Test Methods for Characterization and Improvement to Structural Firefighting Glove Design. (Under the direction of Dr. Roger Lee Barker.)

This research investigates relationships between the construction of structural firefighting gloves and their dexterity and grip performance. Twenty-four structural firefighting gloves and controls are characterized for dexterity and grip performance. Newly developed test methods are compared on the basis of testing variability and ability to provide data that are responsive to differences in glove dexterity and grip performances. Factors of glove materials and construction that affect dexterity and grip performance are identified through these analyses.

This study provides insights into how materials and glove designs affect dexterity and grip performance. Analyses cover layer-, construction- and material- specific aspects of glove design that have a significant effect on dexterity and grip performance. The study indicates ways that structural firefighting gloves can be designed to simultaneously provide improved dexterity and grip performance.

Evaluation of Grip and Dexterity Test Methods for Characterization and Improvement to Structural Firefighting Glove Design

by
Jessica Leigh Watkins

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APPROVED BY:

Dr. Jeff Joines	Dr. Peter Bloomfield

Dr. Roger Lee Barker
Chair of Advisory Committee

BIOGRAPHY

Jessica Leigh Watkins was born August 13, 1987 to Julie Shrauger and Gary Watkins in Statesville, North Carolina. She attended Woodleaf Elementary School in Woodleaf where she grew up and West Rowan Middle and High School where she was actively involved in softball, Junior Civitan, and her Latin Class' Junior Classic League. In the summer of 2004, Jessica was nominated to attend Governor's School for Natural Science at Meredith College in Raleigh where she solidified her love for the sciences and for Raleigh.

In 2005, Jessica was awarded the Spectrum Dyed Yarns Scholarship to the Textiles Program at North Carolina State University where she graduated Suma Cum Laude and Valedictorian with a Bachelor's of Science in Textile Technology in 2009. During her undergraduate study, Jessica worked as a Chemistry 101 tutor for three years and as a Fiber Lab Teacher's Assistant for two years. She enjoyed an internship position at the Hillcrest Nonwovens Plant in South Carolina with Milliken and Co.'s Summer Challenge Program in the summer of 2008. The following summer, Jessica worked on a special project where she designed twisted PVA and CNT yarns and converted them to a woven fabric for aerospace application.

Accepted into the Graduate Program at the College of Textiles in 2009, Jessica was invited to become a part of the research team at the Center for Textile Protection and Comfort at NC State. Here she was fortunate enough to help develop new grip and dexterity test methods for structural firefighting gloves, evaluate the reliability of these tests and utilize them to recommend design improvements to structural firefighting gloves based on. Jessica will graduate with the degree of Master of Science in December of 2011.

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Chapter 1. Introduction

Thermally protective gloves having better dexterity and grip performance is a primary need for structural firefighters. The importance of thermally protective gloves for reducing hand burns is obvious, but often, the need for hazard protection leads to a reduction in hand function. As indicated by available data on firefighter burn injuries, the most common injuries received by firefighters occurred in the arm or hand: 8,115 injuries or 20% of total injuries incurred [1]. Of burn injuries, 29% were localized to the arm or hand region, second only to burns incurred on the head area [1]. The actual number may be higher because mild or first degree burns often go unreported [2]. Many hand burn injuries occur outside of the flame envelope, in which case hands may be extended toward the fire where they experience a high heat exposure. Firefighters may touch hot objects and compress gloves to their skin. They may also receive steam burns to the hands caused by spraying fire and hot objects with water [3].

1.1 Need for Research

In a survey conducted by the NFPA 1971 Technical Committee Task Group on Gloves, the most common attribute firefighters indicated that they disliked about their structural gloves was dexterity performance [4]. Glove bulkiness was identified as the next biggest problem by firefighters, and grip performance was among the top four complaints, as illustrated in Figure 1.1.

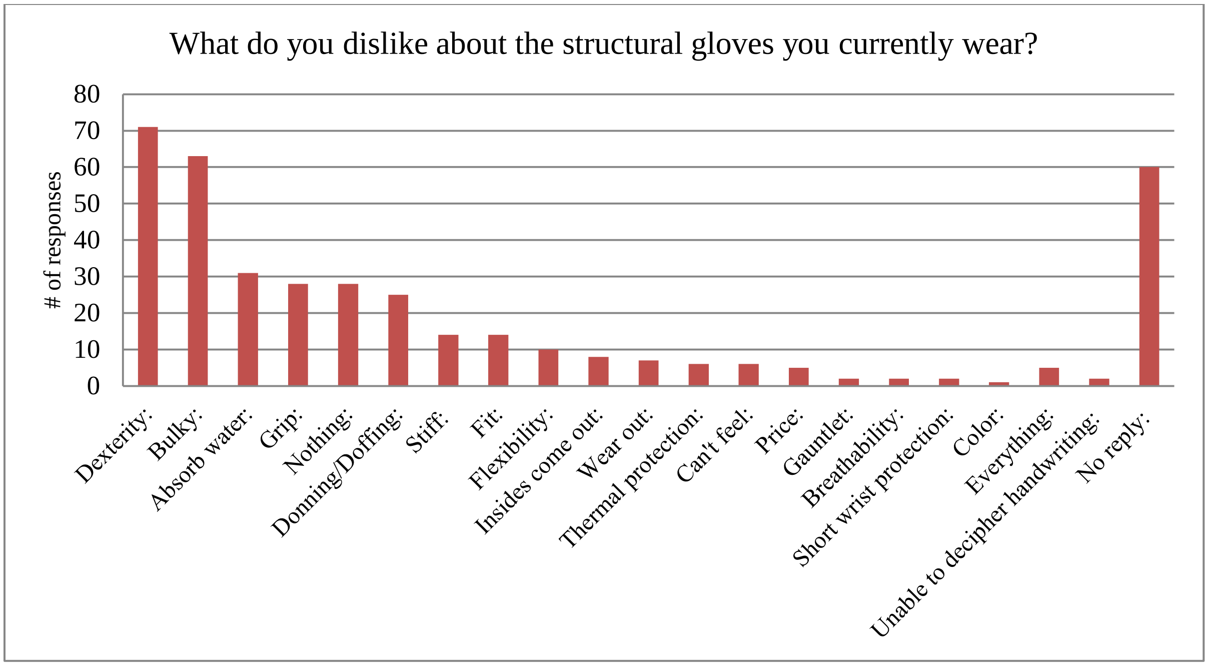

Figure 1.1 Structural Glove Attributes Disliked by Firefighters [4]

Firefighters typically respond to glove performance inadequacies by wearing NFPA 1971 non-compliant gloves, carrying multiple sets of gloves for different tasks or by removing their structural gloves completely. Of the 349 firefighters surveyed, illustrated in Figure 1.2, 72.8% admitted to removing their gloves to change communication radio channels. Forty-two percent removed their gloves to attach hydraulic rescue couplings, and 39.5% when starting two-cycle chain saws. Almost one fourth of firefighters removed their gloves when attaching and detaching buddy breathers under pressure and 20.9% when manipulating Universal RIC fittings.

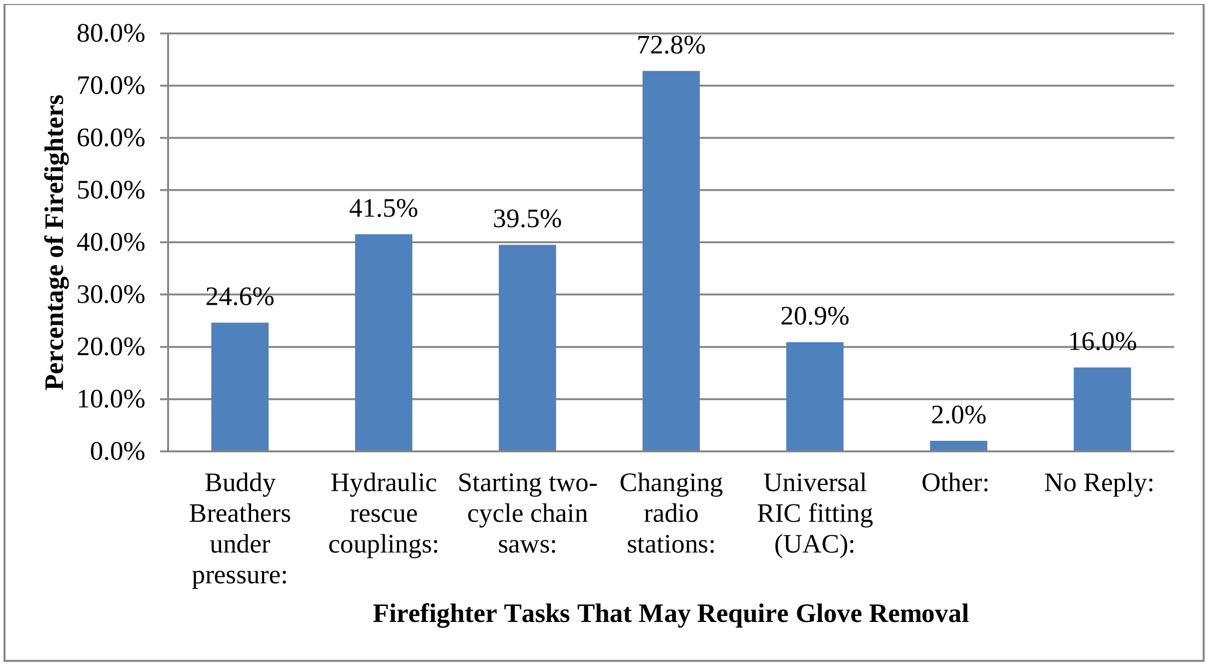

Figure 1.2 Percentage of Firefighters Removing Gloves to Perform Tasks [4]

The understandable emphasis placed on thermal and physical hazard protection performance frequently leads to reduced hand functionality. It is often assumed that bulky glove constructions provide better protection [5]. Bulky glove designs may actually increase hazard by decreasing sensory feedback, range of motion and hand functions related to dexterity and grip.

1.2 Dexterity Study Objectives

This research studied two aspects of structural firefighting glove functionality: dexterity and grip performance. It focused on two aspects of glove dexterity performance: gross dexterity and fine dexterity. Gross dexterity refers to the impact of the glove on the ability to manipulate relatively larger objects with the whole hand. Fine dexterity relates to the impact of the glove on the ability to manipulate small objects with the tips of the fingers. The objectives of the dexterity phase of the study were to:

- Compare different glove dexterity test methods for assessing the dexterity performance of a selected group of structural firefighting gloves.
  - Demonstrate improved, more job-relevant test methods for characterizing structural firefighting glove dexterity functionality.
  - Develop new dexterity test methods that can be used to differentiate between structural firefighting gloves based on their dexterity performance.

These dexterity test methods were used to study the effect of glove materials, constructions and designs on dexterity performance in order to:

  - Develop statistical models that predict a glove's dexterity performance from glove material and design properties.
  - Recommend structural firefighting glove designs for improved dexterity performance.

Chapter 2. Dexterity of Structural Firefighting Gloves

2.1 Dexterity Test Methods

Many tests have been used to characterize the dexterity performance of different types of gloves. Pegboard-type tests are common. The Minnesota Rate of Manipulation Test-Turning involves picking up twenty wooden cylinders from a board, transferring them to the other hand by turning them over and then placing them back into the board [5; 6]. A similar test, the block manipulation test, involves turning over six wooden cubes of varying sizes as quickly as possible [5]. Additional pin-related tests include the Purdue Pegboard Test and the O'Connor Finger Dexterity Test which involves picking up three small pins at once and placing them into a hole [6]. To test the dexterity performance of thin gloves, the Crawford Small Parts Dexterity Test has been used which involves the use of tweezers, small screws and screwdriver [7]. Task or assembly tests have also been implemented to characterize glove dexterity performance. The Bennett Hand Tool Dexterity Test involves a specific set of tools for assembling each set of three different sized bolt/ nut/washer combinations onto a vertical wooden board. Wrenches are used for the two larger sets of bolts, while the smallest bolt requires a screwdriver [6; 8]. Bensel also introduced a Rifle Assembly Test to characterize glove performance in her dexterity study [6]. Other timed task tests use a rope knotting task in which the subject wraps a rope around a one-inch thick dowel and secures it with two free-hand knots [5]. Time-independent tasks have also been employed to test dexterity performance. The divergent rod and two-point discriminator tests deliver a measure of dexterity and tactility performance. The EN 420 standard includes five levels of pin diameter and the indication of whether or not they can be picked up [9]. Even a keyboard test including the number of errors reported has been used as a measure of dexterity. However, many of these tests are designed for very thin gloves or not for gloves at all, but as a human dexterity evaluation tool or as a gauge in physical therapy recovery. No matter the test employed, it has been widely accepted that the used of gloves reduces dexterity performance when compared to the bare hand [5; 8; 9; 10].

Many researchers have found that the measure of gloved dexterity performance depends highly on the type of task or test used to measure it. Plummer found a significant difference in performance time based on the size of bolt manipulated, during the Bennett Hand Tool Dexterity Test [8]. Bradley evaluated eighteen different commercially available gloves and found that the performance of each glove varied widely between five cockpit control operations [10]. Not only did glove performance vary between operations, but certain gloves that performed well in one task performed poorly in another. Bradley attributes these performance trends to the effect of five measured properties of each glove which suggests that dexterity evaluation test methods should be end-use specific [10]. Dodgen et al. compared subjective rankings to objective rankings provided by each of four test methods [9]. They suggest that the most valid test ordered the gloves by performance in a similar fashion as the test participants ordered them [9]. These combined studies indicate that, not only should glove dexterity test methods be end-use specific, but also that they should agree with perceived dexterity performance of the tested gloves.

2.2 NFPA 1971 Test Requirements for Glove Dexterity Performance

The NFPA 1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting is a consensus standard developed by a balanced committee of firefighters, manufacturers and technical experts [4]. The purpose of these standards is to establish minimum levels of protection for firefighter protective ensembles. Hazards addressed include thermal, physical, environmental, and bloodborne pathogens. These standards also establish design and material performance requirements to minimize the effect of these threats [11].

NFPA 1971 prescribes eighteen different test methods for structural firefighting gloves, including twenty-five performance requirements for components. In addition to tests for dexterity, included are five thermal tests, three barrier tests, three mechanical properties tests, a glove donning test, a liner retention test, label durability and legibility test, corrosion resistance, and a grip test.

The first structural firefighting glove dexterity requirement incorporated in the NFPA 1971 standard was the Bennett Hand-Tool Dexterity Test [12]. This test involves disassembling twelve nut/bolt/washer combinations (four of each of three sizes) by hand from one side of a "U"-shaped frame, and reassembling them on the other side using multiple sizes of wrenches and a screwdriver as seen in Figure 2.1. Originally designed as a tool proficiency aptitude test, the Bennett Test measures bare-handed gross motor skills. The NFPA 1971 standard applied this test to evaluate the dexterity performance of structural firefighting gloves by comparing a subject's bare-handed test time to gloved test time as follows:

$$\%\ of\ Barehand\ control = \frac{Dexterity\ test\ time\ (with\ gloves)}{Dexterity\ test\ time\ (without\ gloves)} \times 100$$

Figure 2.1 Bennett Hand-Tool Dexterity Test [13]

The test was not well received as a structural firefighting glove evaluation tool because it required a long test time. It was also considered to provide poor simulation of the tasks actually performed by firefighters.

The modified pegboard test replaced the Bennett Hand-Tool Dexterity Test in the 2000 version of the NFPA 1971 standard [14]. The modified pegboard test, based on work conducted by Dodgen et al., is the current dexterity performance standard for structural firefighting gloves in NFPA 1971: 2007 [9]. This test involves picking up and placing twenty-five knurled pins into a test board designed with a 5- by 5-hole layout.

2.2.1 Limitations and Drawbacks of the Current Glove Dexterity Test Method

The current NFPA 1971 dexterity test may not be a sufficient tool for dexterity evaluation. Dodgen et al. intended to promote the modified pegboard test as the new NFPA 1971 dexterity test [9]. The proposed test was compared to a 2-point discriminator test designed for measuring the tactility of a bare hand, and a dexterity pin test based on the EN 420 standard which involves a binary (yes/no) output of whether or not a gloved hand could pick up a pin of ten varying diameters[15]. Compared to a tactility test and a test with only ten levels, the modified pegboard test appears to be a much better test. However, the study failed to compare the modified pegboard test to the then current hand function test: the Bennett Hand-Tool Dexterity Test.

In addition, this test was proposed to evaluate the dexterity performance of structural firefighting gloves but only one NFPA 1971 compliant structural glove was included in the study. While structural firefighting gloves are traditionally 3-layer gloves, only three of the seven test gloves were 3-layer gloves. Two gloves had two layers and two were only single-layer gloves. The study reported the ability of the modified pegboard test to discriminate between glove dexterity performances, but the test gloves were not comparable to one another. With such a small glove selection, the study would have been wise to include only three-layer gloves or only two-layer gloves, designs that are actually representative of structural firefighting gloves. The ability for a test to discriminate between the dexterity performance of three-layer gloves and one-layer gloves is almost meaningless, especially because one-layer structural firefighting gloves do not exist.

While the study reports the modified pegboard test as a better test than the 2-point discriminator test and a pin pick-up test, it provides no evidence that the test was able to discriminate between the three 3-layer gloves or that the measurement system used was reliable and repeatable. These factors are very important when establishing performance levels for structural firefighting gloves.

2.3 Characterizing the Effects of Gloves on Dexterity Performance

The effect of glove design and material selection on dexterity performance has been studied in a range of gloves used for many end-use applications. Plummer's study on hazardous waste protective gloves found that the use of gloves increased the average test completion time by 15 to 37% compared with barehand performance [8]. These researchers discovered a significant effect of wearing two gloves on one hand; these doubled gloves had significantly longer test completion times that the single layer gloves. Bensel discovered a significant effect of glove thickness in her study of chemical protective gloves. Not surprisingly, as glove thickness increased, dexterity performance decreased as indicated by an increase in completion time [6]. Bradley's study did not show much effect of glove outer material type on dexterity performance [10].

Although many comparative studies have been performed on dexterity tests, little research has been done on tests that are specifically designed to evaluate the dexterity performance of structural firefighting gloves. Since dexterity evaluation test methods should be designed specifically for the end-use, this indicates that a comparative study of methods designed specifically for structural firefighting gloves is needed. In addition, a study is needed to more definitively pinpoint the effects of glove design and materials on dexterity performance of structural firefighting gloves.

Chapter 3. Dexterity Study Experimental Procedures

This research used standard and newly developed dexterity performance test methods to characterize a selected group of structural firefighting gloves. Materials level, whole glove, and glove design properties were characterized to determine the combined effect on glove dexterity performance. An objective of this experimental approach was to identify the best dexterity performance test for structural firefighting gloves, and to study the effects of the glove materials and designs on the measured dexterity performance.

3.1 Test Gloves

This research studied the performance of twenty-four different glove pairs, purchased from ten different manufacturers as shown in Table 3.1. The test group included nineteen NFPA 1971 compliant firefighter gloves and five non-compliant gloves. It included an extrication glove (Glove V), a single-layer leather work glove (Glove Q), a hazmat glove (Glove R), a 2-layer leather law enforcement glove (Glove X) and a rubberized glove designed for lab-work (Glove W). Non-compliant gloves were included because these types of gloves are sometimes worn by firefighters. They were included also to examine the measurement range of the test methods represented in this study. The test group included gloves constructed from a range of materials and constructions. It included widely different composite lay-ups in the palms side and in the back side of the gloves.

Table 3.1 Test Gloves

Glove	Composition of Glove						
	Manu-facturer	Shell (Palm)	Shell (Back)	Moisture Barrier	Thermal Liner	Additional Layer	Com-pliant
A	A	Cow	Cow	PTFE laminated on aramid/para-aramid spunlace	Modacrylic		Y
B	A	Cow	Cow	Thick Polyurethane	Modacrylic		Y
C	A	Cow	Cow	Integrated Moisture Barrier/Thermal Liner	N/A	Between Moisture Barrier and Back Shell	Y
D	A	Elk	Elk	Same as Glove A	Modacrylic		Y
E	A	Elk	Elk	Same as Glove B	Modacrylic		Y
F	A	Elk	Elk	Same as Glove C	N/A	Between Moisture Barrier and Back Shell	Y
G	B	Cow	Cow	Same as Glove A	7 oz. Cotton and SEF		Y
H	C	Cow	Cow	Same as Glove A	SEF Modacrylic		Y
I	C	Cow	Cow	Same as Glove B	SEF Modacrylic		Y
J	B	Pigskin	Cow	Barrier Laminated to Thermal Liner	8 oz. SEF Modacrylic Fleece		Y
K	D	Cow	Cow	Same as Glove C	N/A	Between Moisture Barrier and Back Shell	Y
L	C	Elk	Elk	Same as Glove A	SEF Modacrylic		Y
M	C	Elk	Elk	Same as Glove B	SEF Modacrylic		Y
N	C	Digiroo	Kangaroo	Same as Glove A	Air Spacer Para-aramid/Aramid		Y
O	B	Cow	Simplex 100% Kevlar	Same as Glove C	N/A	Between Moisture Barrier and Back Shell	Y
P	C	Cow	Cow	Same as Glove B	SEF Modacrylic		Y
Q	B	Pigskin	Pigskin	None	None		N
R	E	Kevlar	Kevlar	Impermeable Barrier			N
S	F	Goat	Cow	Breathable Thin Polyurethane	Synthetic Knit		Y
T	F	Kangaroo	Kangaroo	Same as Glove S	Synthetic Knit		Y
U	G	Cow	Cow	Same as Glove A	Para-aramid/Aramid		Y
V	H	Synthetic Leather-like Material and Aramide Fabric	Synthetic Leather-like Material and Aramide Fabric	None	N/A		N
W	I	Rubberized Synthetic Knit	Synthetic Knit	None	N/A		N
X	J	Cow	Cow	None	Para-aramid/Aramid		N

3.2 Glove Dexterity Tests

3.2.1 Human Subject Evaluators

Five human subjects participated in evaluating glove dexterity performance. A right hand-dominant group was used that included four college-age males and one female. Subjects were selected so that the right hand fit a large size glove. Since fit is an important factor in glove function, subjects were selected so that no more than two of the twelve hand measurements were outside of the sizing recommendations for large size gloves, as specified in NFPA 1971 [16]. Detailed hand measurements, and a more detailed description of the hand measurement procedure can be found in Appendix A.

Four different test methods were used to characterize the dexterity performance of the test gloves. A more detailed description of the testing procedures is provided in Appendix A.

3.2.2 Modified Pegboard Test: Knurled Pins

The test glove pairs were tested for hand function following NFPA 1971 Section 8.38, ASTM F 2010: Standard Test Method for Evaluation of Glove Effects on Wearer Hand Dexterity Using a Modified Pegboard Test. This method measures the time that it takes for a subject to place twenty-five pegs in a pegboard both with and without gloves.

Before each test, the pins were spread out to the right of the pegboard as shown in Figure 3.1 (for right-handed subjects). Each test subject used their bare right hand to pick up each pin near the center of the barrel using a pincer motion with the index and thumb. Dexterity time was measured as the time between when the subject touched the first pin and when the subject placed the last pin. The average of these last three dexterity times was used as the baseline dexterity test time (DTT_b). Per the standard, the procedure was repeated with the test subject wearing gloves until the coefficient of variation of the last three repetitions was less than 8%. The average of the last three dexterity times was used as the dexterity time with gloves *(DDT$_g$)*.

The dexterity rating for each glove was determined by comparing the glove dexterity time to the bare-handed baseline time for each subject, as:

$$\%\ of\ Barehand\ control = \frac{DTT_g}{DTT_b} \times 100$$

where:

DTT_g = average of the last three repetitions wearing gloves where the Coefficient of Variation did not exceed 8% (sec) and,

DTT_b = average of the last three repetitions without gloves where the Coefficient of Variation did not exceed 8% (sec).

An average dexterity rating for each of the twenty-four glove pairs was calculated by averaging the percent of barehand control values for each of the five test subjects.

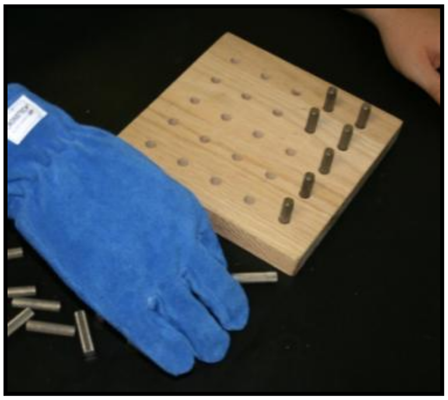

Figure 3.1 Modified Pegboard Dexterity Test: with Knurled Pins

The coefficient of variation was calculated as:

$$cov = \frac{stdev_{last3}}{avg_{last3}} \times 100$$

where:

$stdev_{last3}$= the standard deviation of the last three repetitions and,

avg_{last3} = the average of the last three repetitions.

3.2.3 Modified Pegboard Test: Smooth Pins

The same pegboard test was conducted following ASTM F 2010, except smooth pins were used instead of knurled pins.

3.2.4 Incremental Lift Test

Fine dexterity was measured using a new lift test procedure developed by the Center for Textile Protection and Comfort at North Carolina State University. The method measures the minimum height that a cylinder must be raised above a plane before a subject can successfully lift the cylinder out of the opening in the elevated plane shown in Figure 3.2.

An elevated plane was constructed so that the cylinder supported by an incremental lift system (lab jack) could easily fit underneath. A circular hole was cut into the plane so that as the jack was raised, the cylinder would raise up through the plane. A rod was attached vertically to the lift and emerged through a hole on the top side of the plane. This rod was used as an indicator to ensure that the starting point of the top of the cylinder was always flush with the top of the plane. It was also used to measure the height that the cylinder was raised with the lift as a digital gauge could be zeroed at the point where the cylinder was flush with the plane.

The dexterity rating for each glove was determined by comparing the glove dexterity height to the bare-handed baseline height for each subject, calculated as:

$$\%\ Barehand\ control = \frac{DLH_g}{DLH_b} \times 100$$

where:

DLH_g = minimum of 5 lift heights while wearing gloves (mm), and

DLH_b = minimum of 5 lift heights without wearing gloves (mm).

An average dexterity rating for each of the twenty-four glove pairs was calculated by averaging the percent of barehand control values for each of five test subjects.

Figure 3.2 Incremented Lift Dexterity Test

3.2.5 Tool Test

The tool test, shown in Figure 3.3, measures the time required for a test subject to assemble and tighten a group of bolts, nuts and washers onto a vertical test board [17].

Figure 3.3 Tool Dexterity Test

In this test, the human test subject begins by picking up the first of four bolt/washer assemblies with the left hand and inserting the bolt/washer into the end hole on the top row of the vertical test board assembly. The test facilitator hands a washer to the subject's right hand which the subject places over the end of the bolt. The subject picks up a nut, and while holding the bolt with the left hand, screws the nut onto the end of the bolt with his/her right hand until resistance is met. The subject then picks up the box wrench and uses it to hold the bolt secure while applying 120 inch pounds of force with the torque wrench; a click sound made by the torque wrench indicates that the nut was tight and the subject moves on to the next bolt/washer assembly. This process was continued across the top row of holes, in order, and then to the bottom hole.

Dexterity test time was measured, in seconds, as the time from when the test subject touched the first bolt/washer assembly until the torque wrench clicked on the bottom bolt. The dexterity rating for each glove was determined by comparing the glove dexterity test time to the bare-handed baseline time for each subject as:

$$\%\, Barehand\ control = \frac{DTT_g}{DTT_b} \times 100$$

where:

DTT_g = average of the last three repetitions wearing gloves where the Coefficient of Variation did not exceed 8% (sec), and

DTT_b = average of the last three repetitions without gloves where the Coefficient of Variation did not exceed 8% (sec).

The procedure was repeated until the coefficient of variation of the last three repetitions for each is less than 8 percent.

The coefficient of variation was calculated as:

$$cov = \frac{stdev_{last3}}{avg_{last3}} \times 100$$

where:

$\mathrm{stdev}_{\mathrm{last3}}$= the standard deviation of the last three repetitions, and

$\mathrm{avg}_{\mathrm{last3}}$ = the average of the last three repetitions.

An average dexterity rating for each of the twenty-four glove pairs was calculated by averaging the percent of barehand control values for each of the five test subjects. Additional details concerning this method can be found in Appendix A.

3.3 Characterization of Glove Material Properties

The dexterity performance of structural firefighting gloves depends on the combined effect of material and whole glove design variables. Glove material properties were characterized as follows:

3.3.1 Composite Weight

The weight of the glove composite layers (outer shell, moisture barrier, thermal liner and additional layers) was measured using a Mettler PM1200 precision balance. Swatch sized samples (4 in by 4 in) were die-cut directly from the palm and back sides of test gloves. Whenever the palm and back composite lay-ups were the same, measurements from a sample taken from the back of the glove were made. Composite weight was calculated in ounces per square yard from six replicate measurements.

The weight of each separable layer of the glove composite was measured from 4 in by 4 in samples, die-cut from the palm and back sides of test gloves. Whenever the palm and back composite lay-ups were the same, measurements from a sample taken from the back of the glove were made. Individual layer weight was calculated as the average of six replicate measurements.

3.3.2 Composite Thickness

Thickness of both back and palm composite lay-ups were measured to the nearest hundredth millimeter following ASTM D 1777. An AMES comparator model 99-0697 was used to measure the thickness of 4 in by 4 in samples die-cut from the palm and back sides of the gloves, at a pressure application of 0.6 PSI. An average of six measurements from different samples was recorded as the composite thickness. Whenever the palm and back composite lay-ups were the same, measurements from a sample taken from the back of the glove were made. The thickness of individual material layers in the composite lay-ups was also measured.

3.3.3 Composite Density

The density of the layered glove composites, from both the palm and back sides of the glove, was calculated from measured composite weight and thickness, as follows:

$$\begin{aligned} &Composite\ density\left(\frac{g}{cm^3}\right) \\ &\qquad = Composite\ weight\left(\frac{g}{(4\ in)^2}\right) \times 0.403225 \\ &\qquad \div \frac{1}{Composite\ thickness\ (cm)} \end{aligned}$$

where:

Composite weight is measured as the weight in grams of a 4 inch square sample,

0.403225 is the conversion factor to change the units of composite weight to g/cm^2, and

Composite thickness is the average of three thickness measurements in cm.

3.3.4 Coefficient of Friction

The coefficient of friction of the glove outer shell material was assessed by measureing the angle of slippage against an inclined fiberglass surface, shown in Figure 3.4, three times in two directions for the palm surface of each glove specimen. A 950 gram sled was placed on top of a four by four inch shell sample at a predetermined position on the plane. The incline angle when the sled and shell began to slip was recorded by a digital inclinometer. The tangent of the average of these three measurements was noted at the static coefficient of friction of the material against a fiberglass surface.

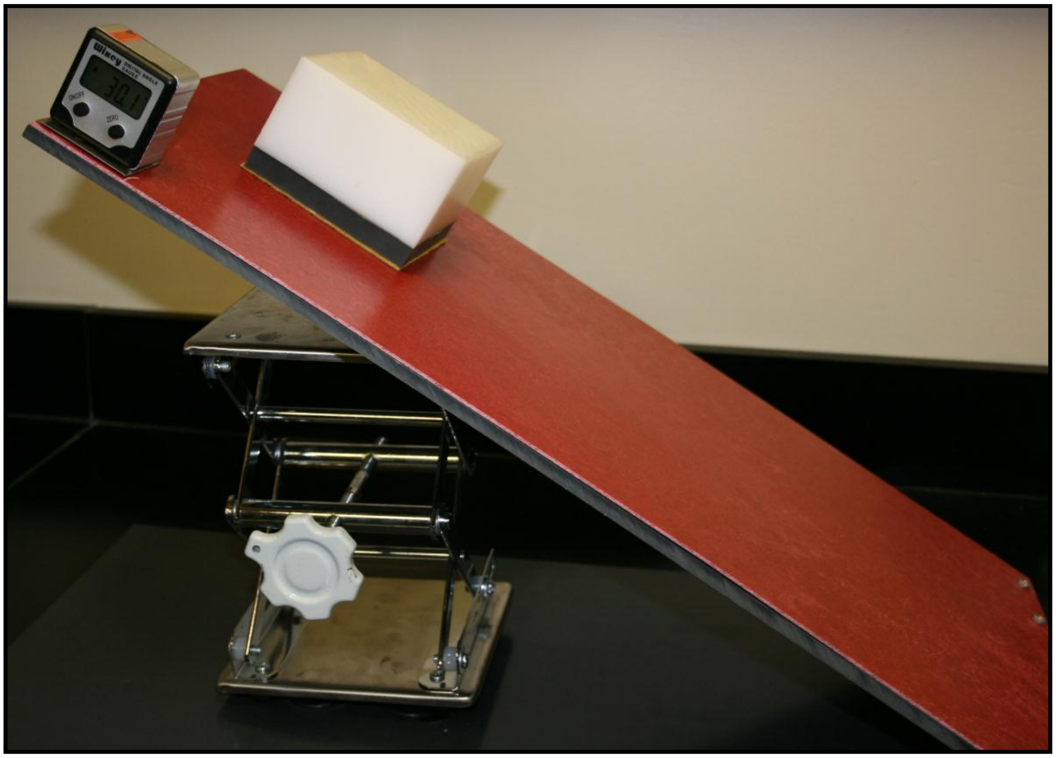

Figure 3.4 Inclined Plane Apparatus for Static Coefficient of Friction Measurement

3.3.5 Material Stiffness

Resistance to bending was measured for the palm and back composites, and also the constituent separable layers of each, for each glove using a modification of ASTM D 4032:

Standard Test Method for Stiffness of Fabric by the Circular Bend Procedure [18]. Die-cut 4 in by 4 in samples were tested (without folding because of thickness) by a Circular Bending Apparatus with a pneumatic actuator for the max force required to plunge the sample through a 1.50-in diameter orifice. Sample face direction was varied between back and palm composites to simulate actual bending direction of composite when in glove form.

3.3.6 Compressive Resilience

Compression resilience (RC, %) was measured with the KES-FB3 Compression Tester at 50gf/ cm^2 at a rate of 1 mm/sec for a 2 cm^2 area of three repetitions of 4 in by 4 in die-cut samples of palm and

back composites of gloves. A higher percentage indicates a higher extent of recovery from compressed thickness to initial thickness [19].

3.3.7 Bending

Bending rigidity (B, gf.cm2/cm) of three repetitions of 4 in by 4 in die-cut sample of palm and back shell materials was measured with the KES-FB2 Bending Tester by bending the sample approximately 150° in a continuously changing arc of constant curvature. Higher values of B indicate a higher resistance to bending or greater stiffness [19].

3.3.8 Roughness

Surface roughness (SMD, microns) of three repetitions of 4 in by 4 in die-cut samples of palm shell materials was measured with the KES-FB4 Surface Tester with an applied tension load of 20 gf/cm. A higher SMD value (average of both forward and backward directions) indicates a rougher surface in the geometric sense [19].

3.3.9 Shear

Shearing stiffness of three repetitions of 4 in by 4 in die-cut samples of palm shell materials was measured by the KES-FB1 Tensile-Shear Tester by application of opposing parallel forces until an offset angle of 8° was reached. The shear stiffness (G, gf/cm.degree) was collected between 0.5 and 2.5 degrees and offset angle. Lower values indicate a softer, more pliable material [19].

3.4 Characterization of Whole Glove Properties

To determine material effects on whole glove properties and whole glove property effects on dexterity performance, whole glove properties were measured as follows:

3.4.1 Glove Volume: Whole Glove Bulk

Glove volume (material and airspace), or bulk, was measured by a water displacement method, as shown in Figure 3.5. The measurement used an open-ended 6-inch inside diameter PVC cylinder.

Clear tubing with a negligible diameter jutted out from the side with an elbow connector and followed the height of the cylinder to be used as a more precise displacement measurement scale. Each test glove was placed on a large hand form and submerged, with the fingers facing downward, to the wrist crease, into the cylinder filled with water to a predetermined height. The change in water height was measured along the clear tubing in millimeters with a caliper. Glove bulk was calculated by subtracting the amount of water displaced by the hand form alone from the hand form/glove ensemble and converted to cubic centimeters by considering the radius of the cylinder, as:

$$Bulk = Height\ (cm)\ \times \pi(7.69112cm)^2$$

where:

Height is the difference in height of vertical water displacement between hand form and hand form/glove ensemble for each glove. Three repetitions of this characterization test were performed.

Figure 3.5 Whole Glove Bulk Measurement

3.4.2 Finger Circumference

The circumference of the index finger of the gloves was measured as shown in Figure 3.6. Finger circumference was measured ¾ inch from the tip of the glove index finger.

Figure 3.6 Measurement of Index Finger Circumference

Thumb circumference was measured ¾ inches from the tip of the thumb.

3.4.3 Glove Stiffness

Glove stiffness/flexibility was measured by the pressure required to close pneumatic hand form to a predetermined point as indicated in Figure 3.7. Calculated from 5 repetitions, the pounds per square inch (lbf /in) of air pressure was recorded (Figure 3.8).

Figure 3.7 Pneumatic Hand Form

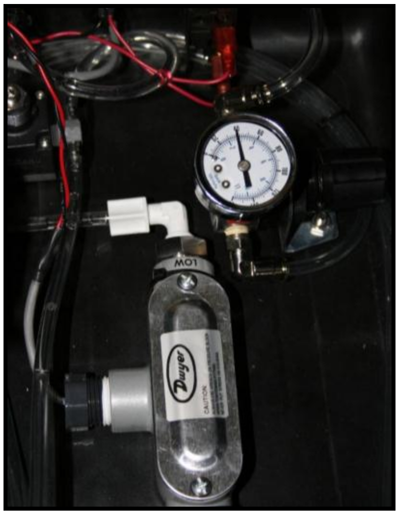

Figure 3.8 Pressure Gauge for Pneumatic Hand Form

3.5 Glove Design and Construction Features

Structural firefighting gloves typically employ a three-layer composite construction consisting of a thermal liner (the layer closest to the hand), a moisture barrier and an outer shell material [11].

3.5.1 Outer Shell Materials

The outer shell of the glove is designed to protect the wearer and the inner layers of the glove from thermal and mechanical hazards. Shell materials must have high puncture, abrasion and cut resistance. Leather is often used because it can withstand repeated flexing without failure [20]. Many different types of leather are used in structural firefighting gloves. The type of leather used depends on the layer from which it is split, the animal from which it comes, and the methods by which it is tanned. Therefore, there can be differences in physical and mechanical properties. Leathers commonly used in structural firefighting gloves include cow, elk, goat, sheep, kangaroo and pig leathers.

Leather consists of a semi-aligned tanned network of long collagen fibrils [20]. The angle of weave of these fibrils differs widely between leather types, and plays a major role in the extension, tensile, abrasion resistance and puncture resistance properties. Leathers with a high angle of weave (where fibrils are more perpendicular to the surface), exhibit more extension properties while they tend to have lower tensile strength and abrasion resistance than other leathers of the same thickness. Leathers with a low angle of weave (where fibrils lie more parallel with the skin surface), particularly kangaroo leathers, can be split more thinly and retain the tensile strength of much thicker cow leathers [21]. Leathers employed in glove shells can be brushed or sueded for a different surface effect. Layered synthetic materials may be used as shell materials on the back side of the glove. Most often, glove composites are homogeneous from back to palm. However, it is becoming increasingly common to employ different composite lay-ups in the palm and the back side of the glove. This allows glove designers to combine protection and function where they are needed.

3.5.2 Moisture Barrier Materials

The second layer in a structural firefighting glove is designed to protect the wearer from bloodborne pathogens and other liquid-based hazards. Because they are designed to be liquid-impermeable, the barriers keep out excess water from the environment. They may be moisture-impermeable or –permeable. Moisture-permeable barriers allow evaporated sweat from the hand to pass through to the outside environment.

3.5.3 Thermal Liner Materials

The thermal liner is designed to feel comfortable next to the skin, and to add thermal insulation. It often traps air in a lofted fleece for added insulation. Modacrylic, aramid and para-aramid blends are commonly used in thermal liner constructions.

3.5.4 Layered Constructions

Structural firefighting gloves are typically composed of three-layer composite lay-ups, but there are exceptions. Some manufacturers provide a glove insert material, designed to act as an integrated moisture barrier/thermal liner layer, reducing the palm composite number of layers to two layers in an effort to improve dexterity performance. When this type of insert is used in the glove composite, additional layers of materials are added to the back of the hand to increase the glove's thermal protective performance in this area. Reinforcement materials may be added to the palm or across the back of the knuckles to add protection and to extend the service life of the glove.

3.5.5 Glove Constructions and Designs

Two glove construction types are most commonly used in the structural glove: the 2-D glove, or Gunn cut, and the 3-D glove, or Fourchette design. Gunn construction is characterized by the second and third fingers set into the palm section by a seam across the bottom of each of the fingers. The back of the glove is made from a single piece. The seams in each finger extend two-thirds of the way toward the back of the hand to reduce wear and seam task interference [9]. A more expensive alternative is the 3-D glove design, which features between-finger fourchettes designed to provide an ergonomic or natural fit that contours to the hand. Examples of these glove designs are shown in Figure 3.9.

Gunn Cut (2-D) Design

Fourchette (3-D) Design

Figure 3.9 Structural Firefighting Glove Constructions

3.5.6 Thumb Designs

Figure 3.10 illustrates three common thumb construction designs used in structural firefighting gloves. The straight thumb and wing thumb designs feature relaxed configurations. The straight thumb opens toward the tips of the fingers, and is sewn into the palm as a separate piece. The wing thumb opens away from the palm to the side of the hand, and is one piece with the palm shell. The keystone thumb uses a more natural thumb position than either the straight or the wing thumbs. This design features a separate 3-D structure pieced into the glove in a natural relaxed thumb state.

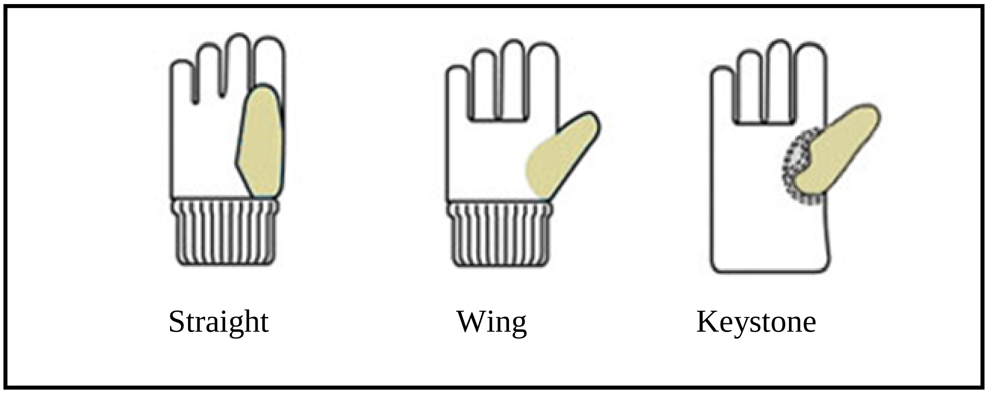

Figure 3.10 Glove Thumb Designs

3.5.7 Insert Connections

The liner retention test in NFPA 1971 requires that the layers from which the glove is constructed must not separate or pull out during use [11]. Insert connections are used to provide this functionality. Figure 3.11 shows the types of connections used between moisture barriers and the outer shell layer. When moisture barriers are sewn to the shell the moisture barrier beyond the seal must not be punctured. Tabs are often connected with adhesive to the moisture barrier which is used as the sewing substrate.

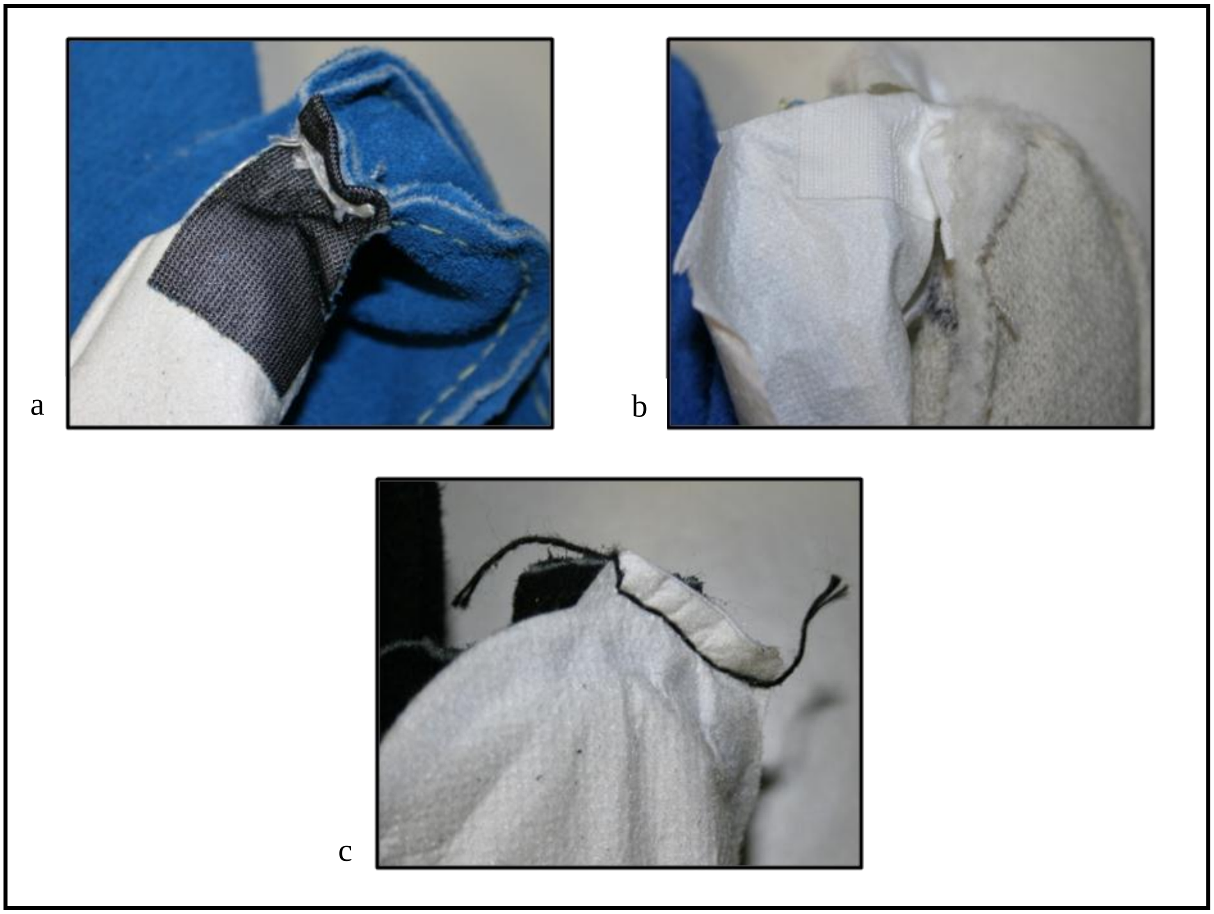

Figure 3.11 Moisture Barrier to Shell Connections (a: Tabs Sewn to Tip, b: Tabs Sewn to Side, c: Sewn to Tip)

Figure 3.12 shows the thermal liner to moisture barrier connection, when there is a third layer. Sometimes the layers are spot glued together. Moisture barriers and the thermal liners are often attached using an adhesive impregnated nonwoven tape.

Figure 3.12 Thermal Liner to Moisture Barrier Connections: (d: Adhesive, e: Double-Sided Tape)

Chapter 4. Dexterity Study Results and Discussion

Four dexterity tests were performed in an effort to evaluate the dexterity performance of structural firefighting gloves. The test methods were compared, and used to analyze the effects of glove materials and constructions on dexterity.

4.1 Dexterity Performance Assessed Using the NFPA 1971 Pegboard Method

To pass the knurled pins pegboard dexterity performance requirement, NFPA 1971 compliant gloves should have an average percent barehand control not exceeding 250 percent [16]. Figure 4.1 shows that the entire group of NFPA 1971 compliant and non-compliant gloves pass this requirement. These results show that, based on firefighter complaints about glove dexterity, the method currently called for by the NFPA standard, does not provide sufficient differentiation of glove performance. These findings clearly indicate the need for a better measurement of glove dexterity performance.

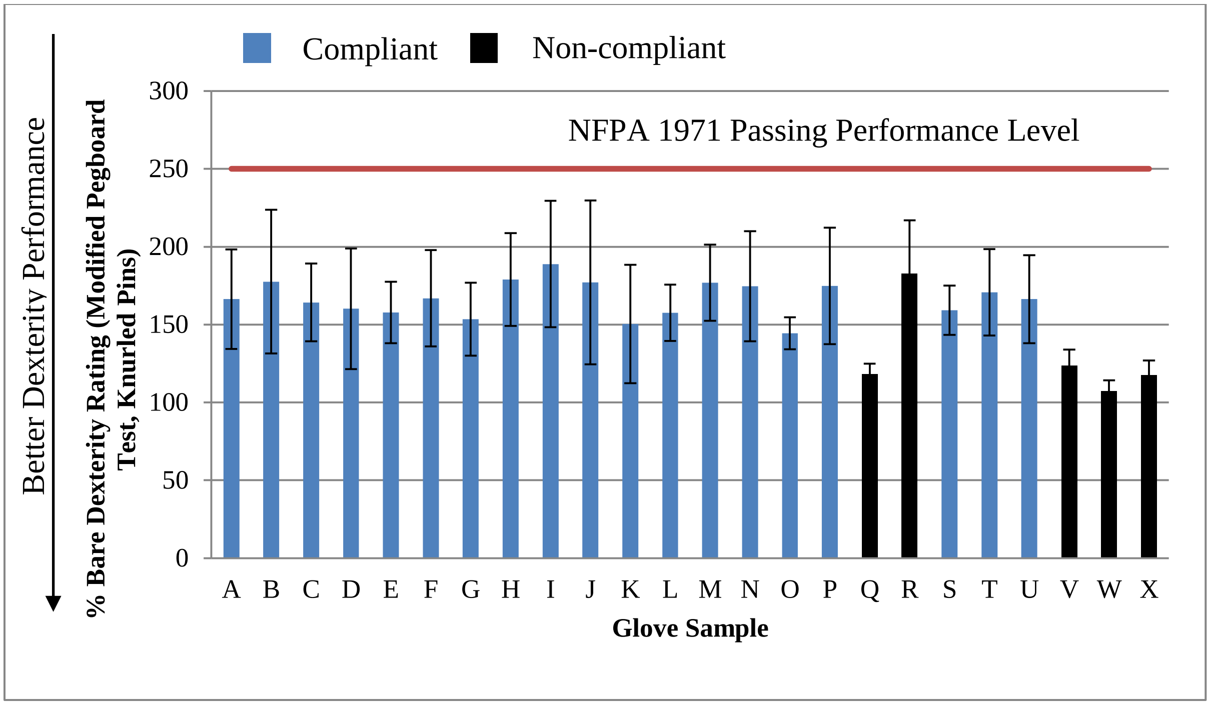

Figure 4.1 Glove Dexterity Measured using Modified Pegboard Test with Knurled Pins (Avg. of 5 test subjects)[1][2]

4.2 Comparing Dexterity Test Methods Based on Variability and Ability to Differentiate Glove Performance

For a test method to be reliable, it must provide low subject-to-subject variability, high discriminating power and, ideally, capture a wide range of dexterity performance. When a test method shows a greater range, it is easier to discriminate between gloves based on their dexterity performance. Discerning if gloves perform differently is important, not only for establishing minimum performance requirements, but also for developing better performing glove designs. If differences in glove performance can be quantified, then differences can be related to materials and design factors. The best way to achieve this goal is to design test

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[1] Gloves with dexterity ratings that fall below the performance limit line pass the NFPA 1971: 2007 standard
[2] Error bars represent the standard deviation of dexterity ratings for five subjects.

methods that provide low subject-to-subject variability while collecting some measurement of dexterity.

4.2.1 Evaluation of Test Measurement Range

Figure 4.2 compares the measurement ranges of the different dexterity tests. To compare the measurement ranges of each of the dexterity tests, the minimum dexterity rating was subtracted from the maximum rating in each test to obtain the range. When considering only the NFPA 1971 compliant gloves, the modified pegboard test with smooth pins captures the largest range of 290. The current test, the pegboard with knurled pins and the incremented lift test capture comparable ranges and the tool test captures the smallest range at 54. A test method capable of evaluating a large range of measurements helps a test method discriminate between gloves because the values are spread over a larger range. When considering only this analysis, the pegboard test with smooth pins seems to be the better test.

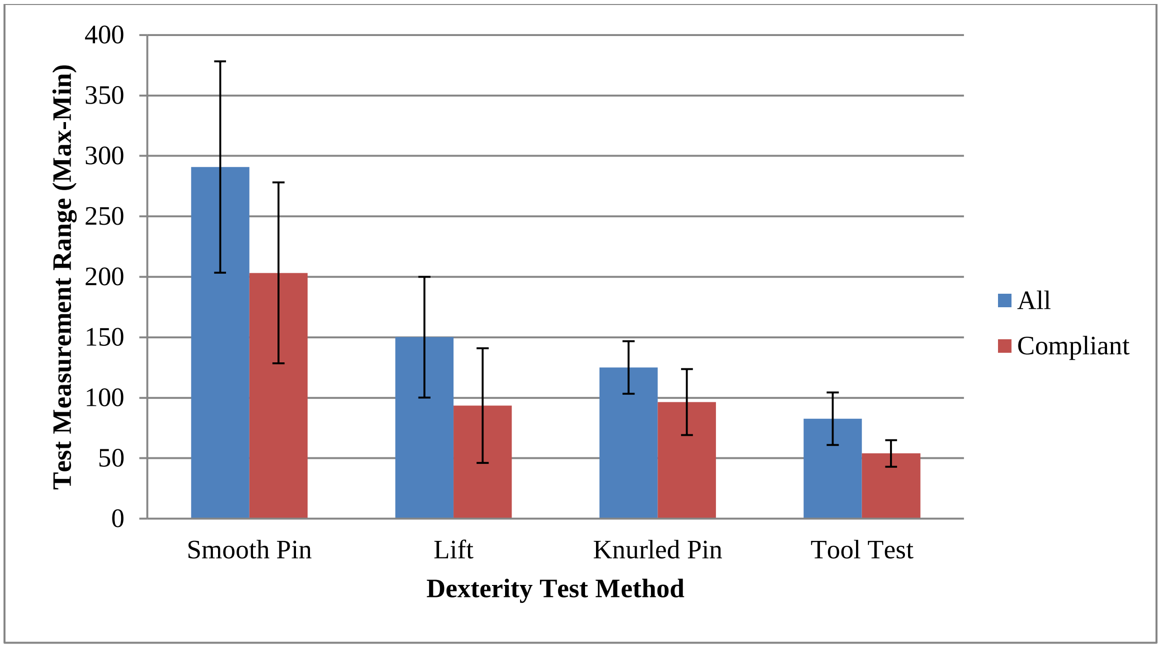

Figure 4.2 Measurement Range of Dexterity Tests for NFPA 1971 Compliant Gloves[3]

However, when considering both the NFPA 1971 compliant gloves and the non-compliant gloves, all the tests capture a much larger dexterity performance range, the smooth pin test still capturing the largest, as 290. The tool test and the knurled pin test capture comparable ranges, but it is important to note that the incremented lift test is shown to capture a much better range when the non-compliant gloves are included. This indicates the ability of the incremented lift test to differentiate dexterous gloves, a quality that will become increasingly important as more dexterous gloves become available to firefighters.

4.2.2 Evaluating the Discriminating Power of Dexterity Test Methods

Since the ranges represented in Figure 4.2 are based on average dexterity ratings, it is important to determine how closely ratings agree between different test subjects. Providing a

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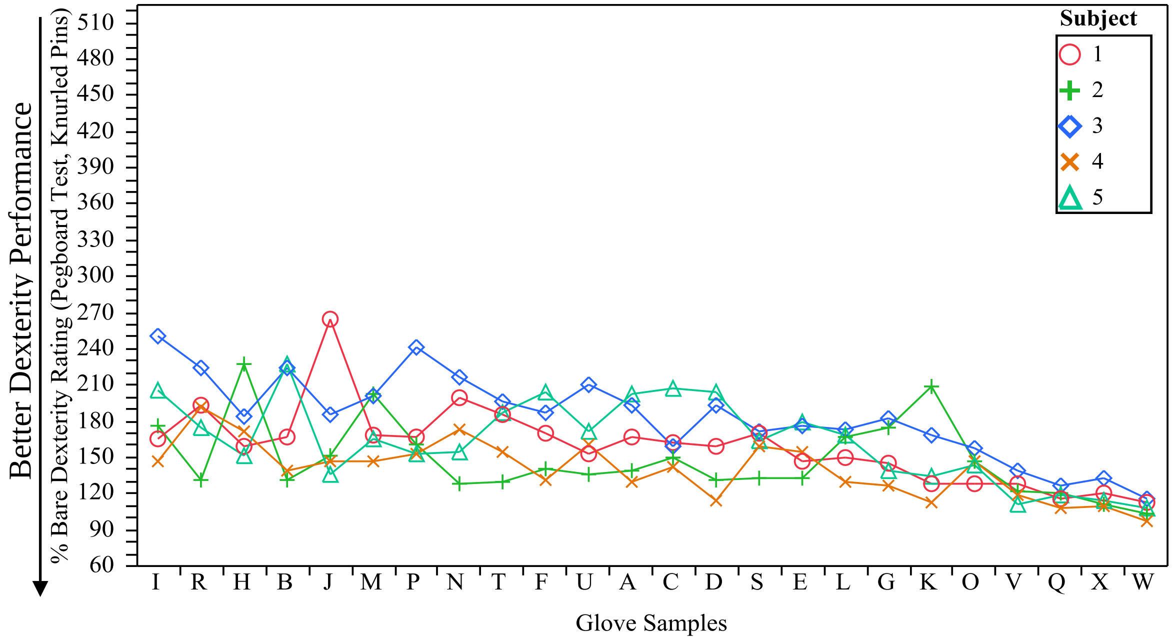
[3] Error bars represent the average standard deviation of the range measurements for each of five subjects.

large measurement range is only one factor in good glove differentiation based on dexterity performance. In addition, tests should be reproducible so that the subject-to-subject variability among dexterity ratings is low.

Table 4.1 provides a summary of the test variability within each dexterity method. The standard deviations represented in this table are based on an average of the dexterity rating standard deviations of all gloves in the group. These data show that the tool and lift tests are less variable than the pegboard tests. T-tests were performed on the group of NFPA 1971 compliant gloves and also on the entire group of gloves. In both cases, the tool test was able to differentiate between glove dexterity much better than the other dexterity tests. The lift test was also able to differentiate between gloves better than the two pegboard tests.

Table 4.1 Dexterity Test Method Variability

Dexterity Tests	Compliant Gloves		Levels of Discrimination	All Gloves		Levels of Discrimination
	Avg. SD	Avg. %CV	t-tests at 95% confidence level	Avg. SD	Avg. %CV	t-tests at 95% confidence level
Tool	17.88	14.16	4	17.62	14.13	9
Lift	27.12	13.43	2	25.26	13.30	7
Knurled Pins	30.24	17.97	2	26.75	16.19	6
Smooth Pins	57.65	24.86	2	53.57	23.81	6



Level	6																					F	F	F	F
	5																		E	E	E	E	E	E	
	4														D	D	D	D	D	D	D	D			
	3			C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C				
	2		B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B					
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A						
Avg.		188.9	182.9	178.9	177.6	177.2	176.9	174.6	174.8	170.7	166.9	166.3	166.3	164.2	160.2	159.3	157.8	157.6	153.4	150.4	144.4	123.7	118.1	117.6	107.4

Figure 4.3 Subject-to-Subject Variability within Pegboard Test with Knurled Pins[4]

The student's t-test was used to identify the dexterity test method with the least variability and as a result, the most discriminating power. Data presented in Figure 4.3 through Figure 4.6 show that the incremental lift test and the tool test produce lower subject-to-subject variability than the pegboard tests. A connecting letters report accompanies the graphical analysis and provides detailed information about which gloves are similar to one another. A higher number of distinguishable dexterity levels (as indicated by the number of

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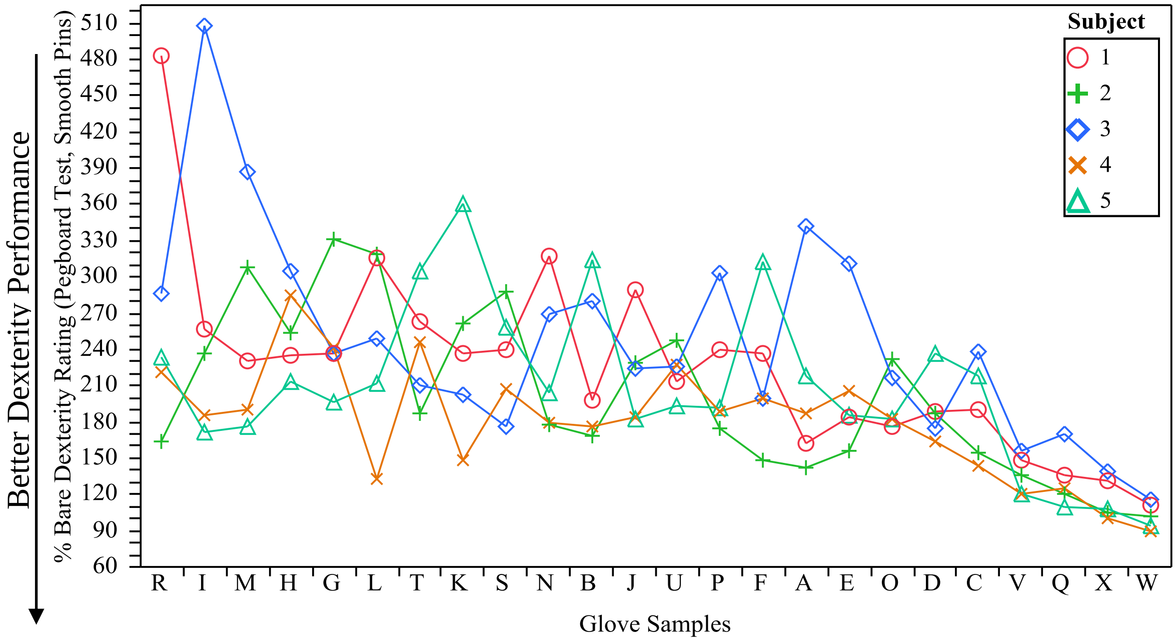
[4] Connecting letters report is provided by collection of student's t-tests performed at the alpha=0.05 significance level. Gloves connected by the same letter do not have significantly different dexterity performances.

letters) is the best indication of low variability within a test method, and therefore more discriminating power.

These analyses show that both pegboard tests provide only six distinguishable dexterity levels. When measured by the pegboard test with knurled pins, seventeen of the nineteen compliant gloves are not significantly different from one another. This means that the pegboard test with knurled pins would show that these seventeen gloves have indistinguishable dexterity performances; not one being any better or worse than another. The smooth pin test performs only slightly better, by distinguishing one more glove from the rest of the compliant pairs.



Level	R	I	M	H	G	L	T	K	S	N	B	J	U	P	F	A	E	O	D	C	V	Q	X	W
6																					F	F	F	F
5																			E	E	E	E	E	
4																D	D	D	D	D	D	D		
3			C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C				
2		B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B						
1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A							
Avg.	277.9	271.9	258.5	258.2	248.4	245.6	242.3	241.5	233.9	229.0	227.1	221.6	221.5	220.2	219.4	210.2	208.4	197.9	189.9	188.8	136.2	132.6	116.7	102.7

Figure 4.4 Subject-to-Subject Variability within Pegboard Test with Smooth Pins[5]

The incremental lift test method, on the other hand, identifies seven statistically distinguishable dexterity levels, while the tool test method defines nine distinguishable dexterity levels. This finding indicates both of these test methods have low enough subject-to-subject variability to distinguish non-compliant gloves from compliant gloves and also compliant gloves from each other.

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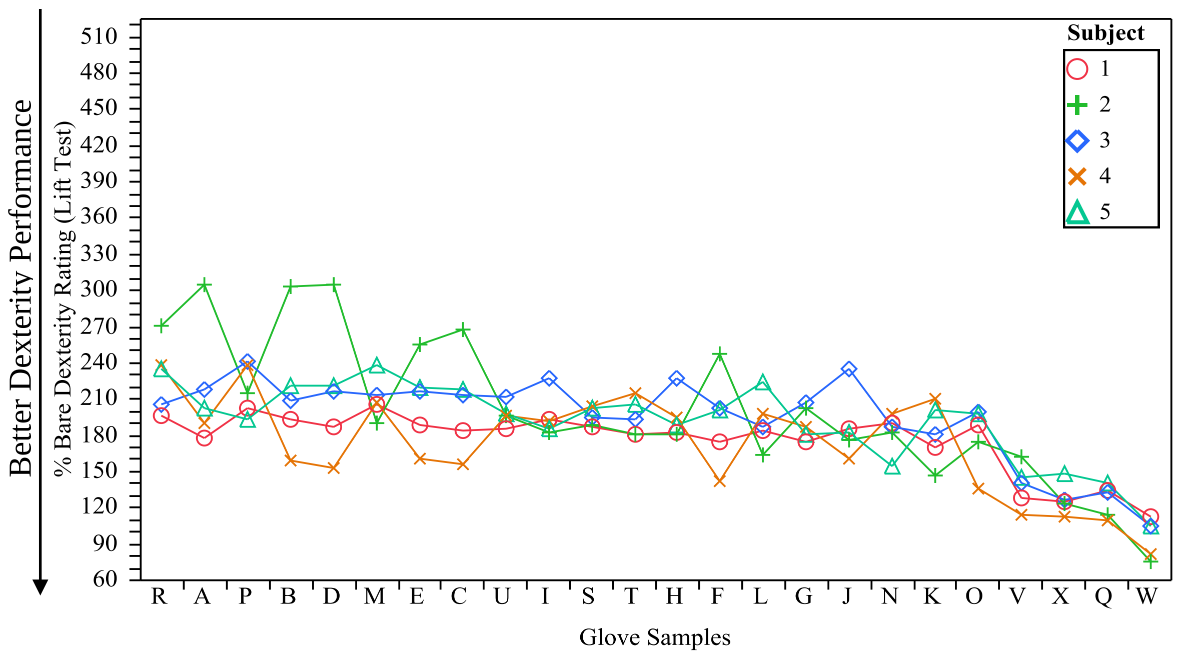
[5] Connecting letters report is provided by collection of student's t-tests performed at the alpha=0.05 significance level. Gloves connected by the same letter do not have significantly different dexterity performances.



Level 7																						G	G	G
Level 6																					F	F	F	
Level 5						E	E	E	E	E	E	E	E	E	E	E	E	E	E	E				
Level 4					D	D	D	D	D	D	D	D	D	D	D	D	D	D	D					
Level 3			C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C						
Level 2		B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B							
Level 1	A	A	A	A	A	A	A	A	A	A	A	A	A	A										
Avg.	229.2	218.7	218.1	217.4	216.6	211.4	208.1	207.5	197.4	196.4	195.4	195.3	195.0	193.4	191.3	190.4	187.8	182.6	181.8	178.9	137.8	127.7	126.6	95.8

Figure 4.5 Subject-to-Subject Variability within Incremental Lift Test[6]

T-test analyses indicate that the tool test and the incremental lift test are the least variable test methods. The fact that the tool and lift tests have smaller measurement ranges than the smooth pin pegboard test points even more at the low variability of these test methods. These methods, therefore, have the greatest ability to recognize differences in dexterity performance.

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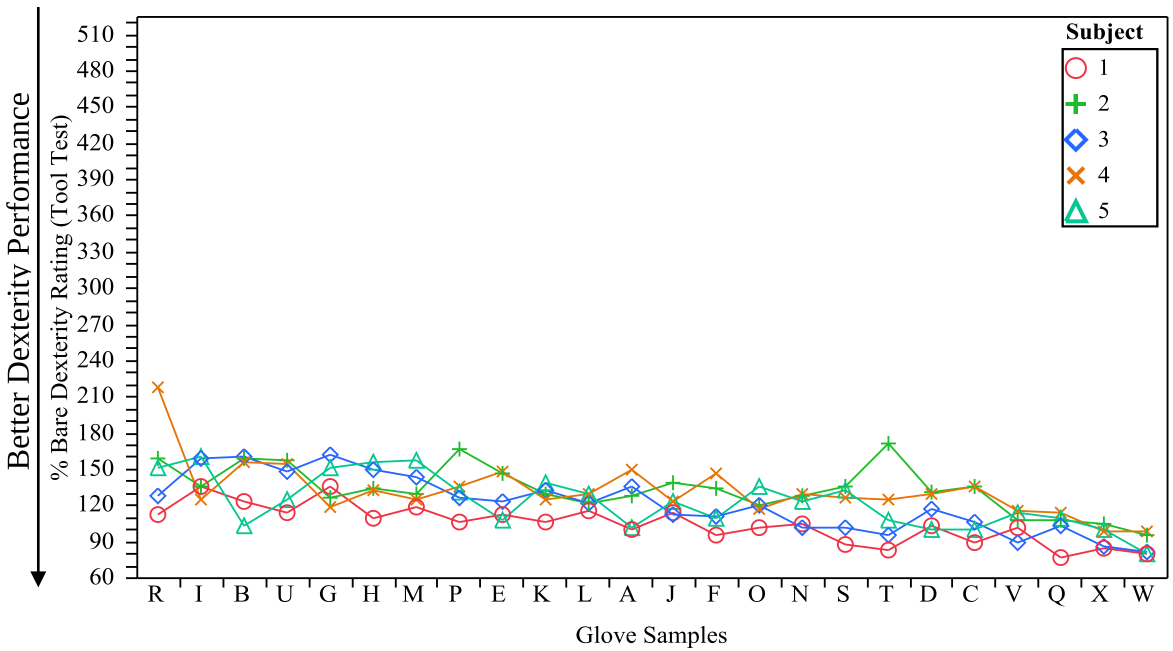
[6] Connecting letters report is provided by collection of student's t-tests performed at the alpha=0.05 significance level. Gloves connected by the same letter do not have significantly different dexterity performances.



Level																								
9																					I	I	I	I
8																H	H	H	H	H	H	H	H	
7											G	G	G	G	G	G	G	G	G	G	G	G		
6									F	F	F	F	F	F	F	F	F	F	F	F	F			
5						E	E	E	E	E	E	E	E	E	E	E	E	E	E	E				
4				D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D					
3			C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C						
2		B	B	B	B	B	B	B	B	B	B	B	B	B										
1	A	A	A	A	A	A	A	A																
Avg.	153.7	143.7	140.7	140.2	139.1	136.5	134.9	133.4	127.7	126.7	123.9	123.4	122.4	119.7	119.2	117.7	117.3	117.0	116.4	113.9	105.9	102.4	95.0	87.6

Figure 4.6 Subject-to-Subject Variability within Tool Test[7]

4.2.3 Correlation Between Objective Measures and Subjective Perception of Glove Dexterity Performance

After they completed all four dexterity tests, subjects were asked to rank test gloves from worst to best, based on their perception of overall dexterity performance. These five sets of rankings were averaged to obtain a subjective rank for each test glove. These numeric

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[7] Connecting letters report is provided by collection of student's t-tests performed at the alpha=0.05 significance level. Gloves connected by the same letter do not have significantly different dexterity performances.

rankings were compared to the rankings based on glove performance in the dexterity tests. Correlation analysis was performed to determine the relationships observed between objective measured and perceived dexterity performance.

The pegboard test with smooth pins was the worst representation of perceived dexterity performance with a Pearson's correlation coefficient of only 0.39, likely because the test was so lengthy and difficult to perform for most gloves. The pegboard test with knurled pins and the tool test provided much better and similar correlations at r = 0.62 and r = 0.61 respectively. However, the lift test agrees best with subjective perception of glove dexterity performance with a Pearson's correlation coefficient of 0.73. This is likely because the lift test is a time-independent test.

Table 4.2 Objective/Subjective Dexterity Correlation Summary Table

	Objective Dexterity Measurement Correlation with Subjective Dexterity Perception			
	Pegboard, Smooth Pins	Tool Test	Pegboard Test, Knurled Pins	Lift Test
Pearson's Correlation Coefficient	0.39	0.61	0.62	0.73

Firefighters currently perceive their structural gloves to have poor dexterity. Identifying a test that has the ability to measure dexterity ratings of gloves that correspond with perceived dexterity is a valuable tool for designing better structural gloves and evaluating current gloves.

4.3 Comparing the Incremental Lift and Tool Dexterity Tests

Since the incremental lift and the tool tests proved more reliable data than the pegboard tests, a correlation was conducted to qualify the agreement between these two test methods. Table 4.3 summarizes the correlation between the lift test and the tool test, where the Pearson's and Spearman's Correlation Coefficients and were calculated for the entire group of test gloves, and for the compliant gloves. For the entire group of gloves, while the Pearson's Correlation Coefficient of dexterity performance as measured by the two tests is moderate to high at 0.7982, the Spearman's Correlation Coefficient of 0.5913 is in the moderate range. These methods agree at extreme levels of dexterity performance, but are much different when considering moderate levels of dexterity performance. This is indicated by the "cloud" of points in the center of the line of fit as seen in Figure 4.7.

Table 4.3 Lift Test/Tool Test Correlation Summary Table

	Correlation between Lift Test and Tool Test	
	Pearson's Correlation Coefficient[8]	Spearman's Rho[9]
Non-Compliant & Compliant	0.7982	0.5913
Compliant Only	0.3932	0.2947

The idea that the lift test and the tool test measure different aspects of dexterity is even more apparent when a correlation analysis is performed on only the group of compliant gloves. The low Pearson's Correlation Coefficient, 0.3932 and Spearman's Rho, 0.2947, shown in Table 4.3, indicate that these tests have little linear agreement when measuring

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[8] Degree of agreement on a scale from 0 to 1

[9] Degree of agreement calculated on the rank of values instead of values themselves

NFPA 1971 compliant gloves. These values and Figure 4.7 indicate that while both of these tests are reliable, they are measuring different aspects of dexterity performance. The lift test can be considered as a measurement of fine dexterity because only the fingertips are used to perform this task. On the other hand, the tool test involves the use of the whole hand (gross dexterity) and the fingertips (fine dexterity) to manipulate large and small objects alike.

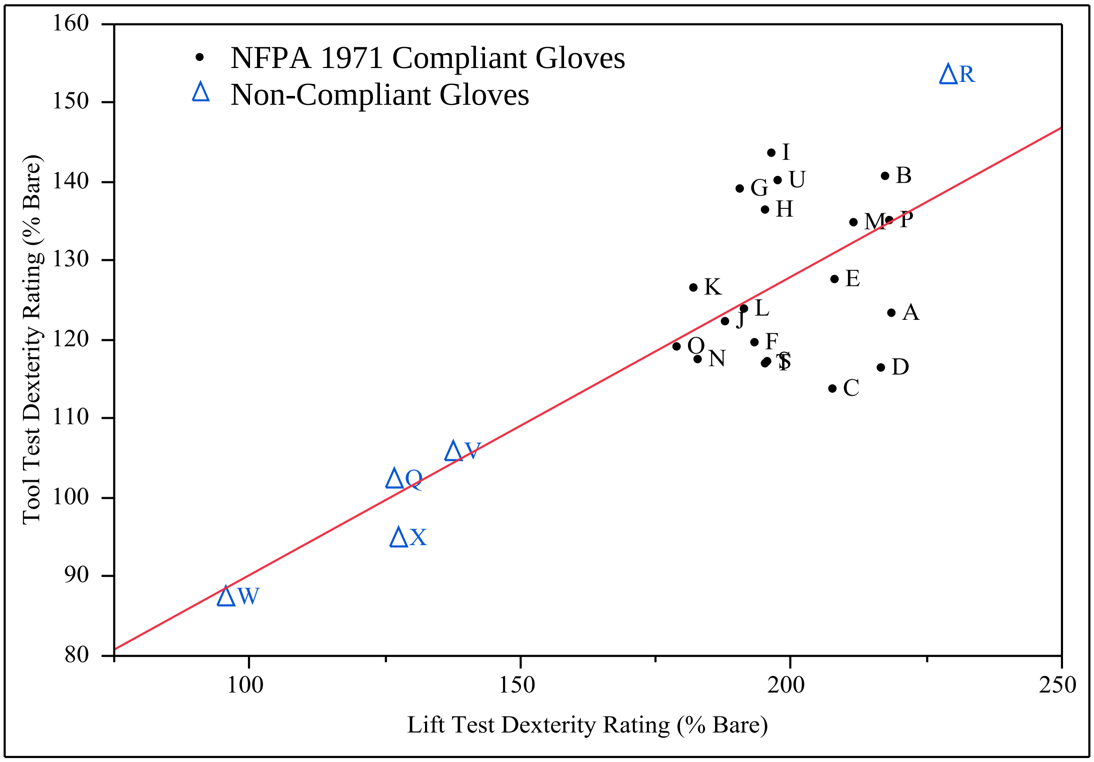

Figure 4.7 Tool Test and Incremented Lift Test Correlation by Glove Dexterity Rating

Because the two tests are measuring different aspects of dexterity, some gloves deviate from the relationship between the incremental lift test and tool test dexterity ratings. Gloves A, C and D perform better in the tool test than in the incremental lift test. Other gloves (G, H, I and U) perform better in the tool test (Figure 4.7). The following discussion discusses the reasons behind these deviations from the relationship.

4.3.1 Factors Affecting Glove Performance Assessed in the Incremental Lift Test

Since the incremental lift test requires little range of motion and involves only picking up an object with the fingertips, the information provided is mainly localized to the fingertip dexterity of the glove. Figure 4.8 shows the dexterity ratings for each of the NFPA 1971 compliant gloves in order of decreasing dexterity performance in the lift test.

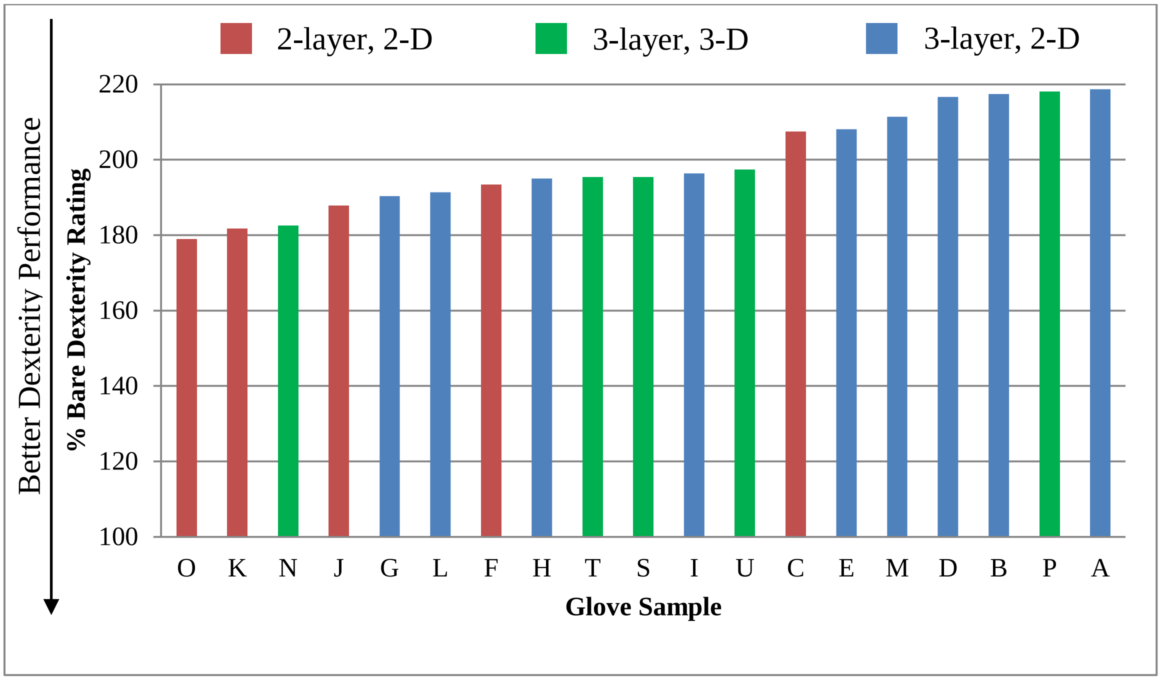

Figure 4.8 Lift Test Dexterity Performance of NFPA 1971 Compliant Gloves

The lift test, a measure of fine dexterity, groups almost all of the 2-layer palm composite gloves within the best seven performing gloves, three of them (O, K, J) within the best four performing gloves. All of these 2-D gloves utilize an integrated moisture barrier/thermal liner layer which makes them 2-layer gloves. This graphical analysis indicates a beneficial effect on dexterity performance can be obtained by reducing the number of layers used in the construction of the palm of the glove.

However, reducing the number of layers in the palm of gloves is not the only way to achieve good lift test dexterity performance. Most firefighting gloves have comparable composite thicknesses in the palm area to meet thermal protection requirements. Palm composite lay-ups use an outer leather shell, a moisture barrier and a thermal liner (or an integrated moisture barrier/thermal liner layer). A more compressible palm composite can be achieved by reducing the leather shell thickness while increasing thermal liner thickness. This design includes a thinner leather layer which is only slightly compressible because of its high density. The thicker thermal liner adds thickness and loft to the entire composite, but allows for compressibility because of its low density and ability to trap air. This palm composite design has a beneficial effect on dexterity performance. For example, Glove N is a 3-layer, 3-D glove, with such a compressible palm composite construction, and performs well in the lift dexterity test as shown in Figure 4.8.

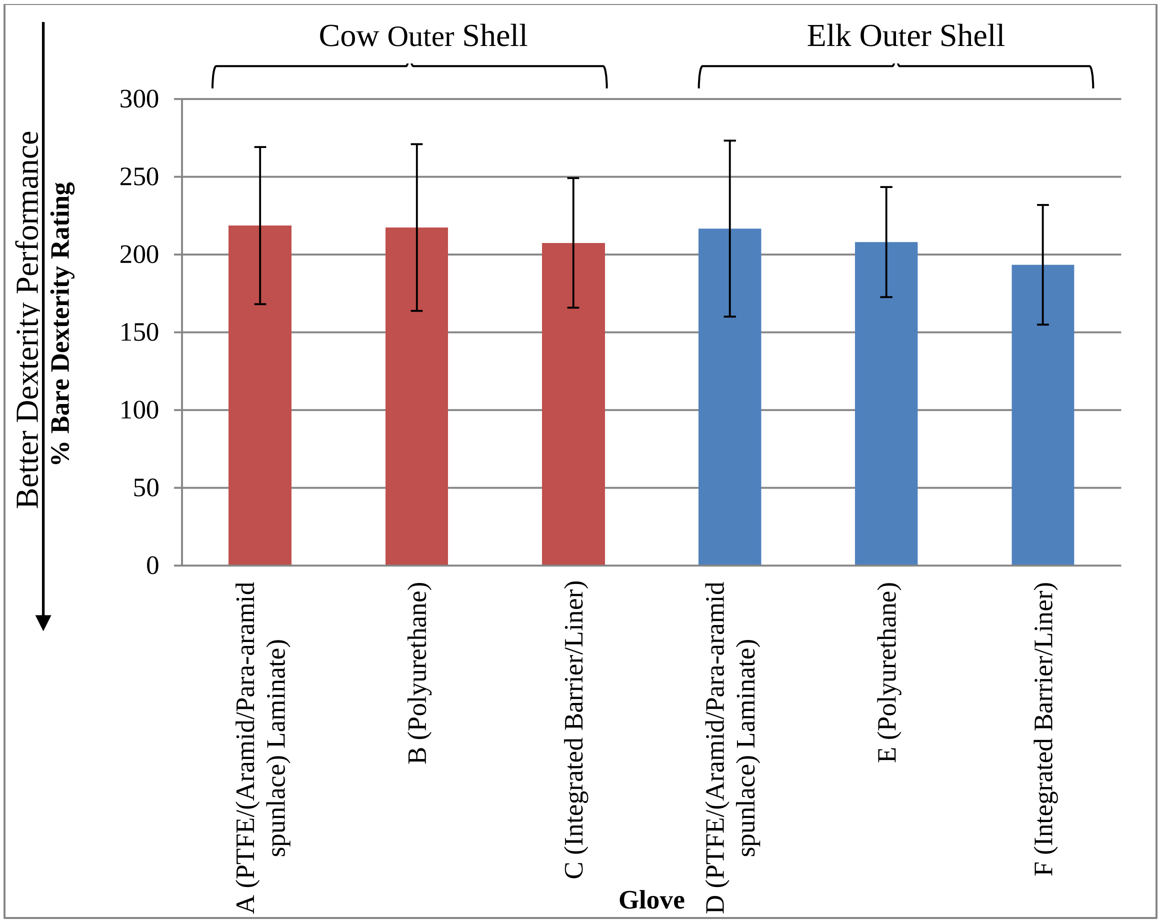

Figure 4.9 Effect of Moisture Barrier on Glove Lift Test Dexterity Performance (Gunn Cut Glove Designs) [10]

Figure 4.9 shows the effect of the moisture barrier component and the type of outer shell leather on glove dexterity in the lift test. It compares six gloves from the same manufacturer having the same exact design but made with different moisture barriers. Moisture barrier effects were compared in gloves made with either cow or elk leather outer shells. For this group, the elk-shelled gloves (D, E, F) performed better in the lift test than their cow-shelled moisture barrier counterparts (A, B, C). Within this construction-

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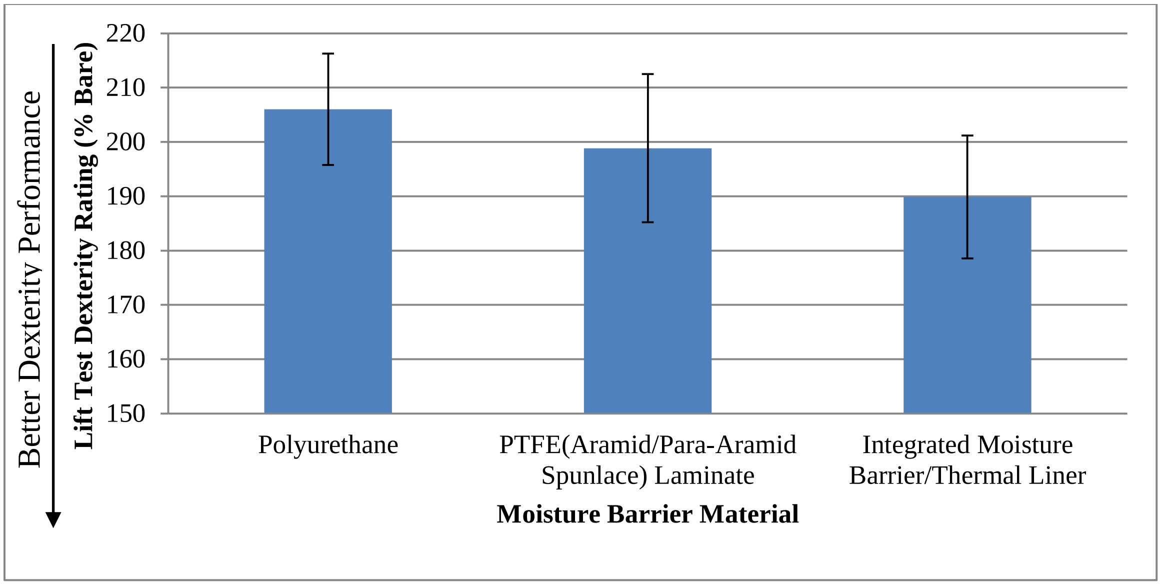
[10] Error bars represent the standard deviation ofdexterity ratings of five subjects.

controlled group, gloves with an integrated moisture barrier/thermal liner performed best (Gloves C and F). These gloves effectively have a 2-layer palm composite while gloves made with PTFE(aramid/para-aramind spunlace) laminate and polyurethane barriers have 3-layer palm composites. Within this subgroup, gloves with polyurethane barriers (Gloves B and E) performed better than those with PTFE(aramid/para-aramind spunlace) laminate barriers (Gloves A and D).

Figure 4.10 shows the effect of the moisture barrier component on the lift test dexterity performance of the nineteen compliant gloves. It also shows that gloves incorporating an integrated moisture barrier/thermal liner typically perform best in this test. However, contradictory to the glove test group in Figure 4.9, this glove test group encompasses a range of constructions and shell materials. This analysis indicates that gloves with polyurethane moisture barriers (and not PTFE(aramid/para-aramind spunlace) barriers) are the worst performers in the lift test. This contradicts the effect of moisture barrier on the dexterity performance within the design-constant six glove subgroup. Consequently, there is evidence to suggest that there are additional design and material factors (besides moisture barrier) that strongly affect dexterity performance.



Level	2		B	B
	1	A	A	

Figure 4.10 Effect of Moisture Barrier on Lift Test Dexterity Performance[11][12]

The main constructional difference between the moisture barrier/thermal liner combination and polyurethane and PTFE(aramid/para-aramind spunlace) laminate barriers is that the integrated moisture barrier/thermal liner combines the barrier technology with a thermal liner making the final composite 2-layer while the other two are barriers alone and make 3-layer composites. It is logical that 2-layer palm composite constructions perform better than 3-layer palm composite constructions in fine dexterity. Figure 4.11 shows the effect of the number of layers in the palm composite on fine dexterity. T-test data indicates that gloves with a 2-layer palm composite construction will perform better (with 95% confidence) on the lift than gloves with 3-layer palm composites.

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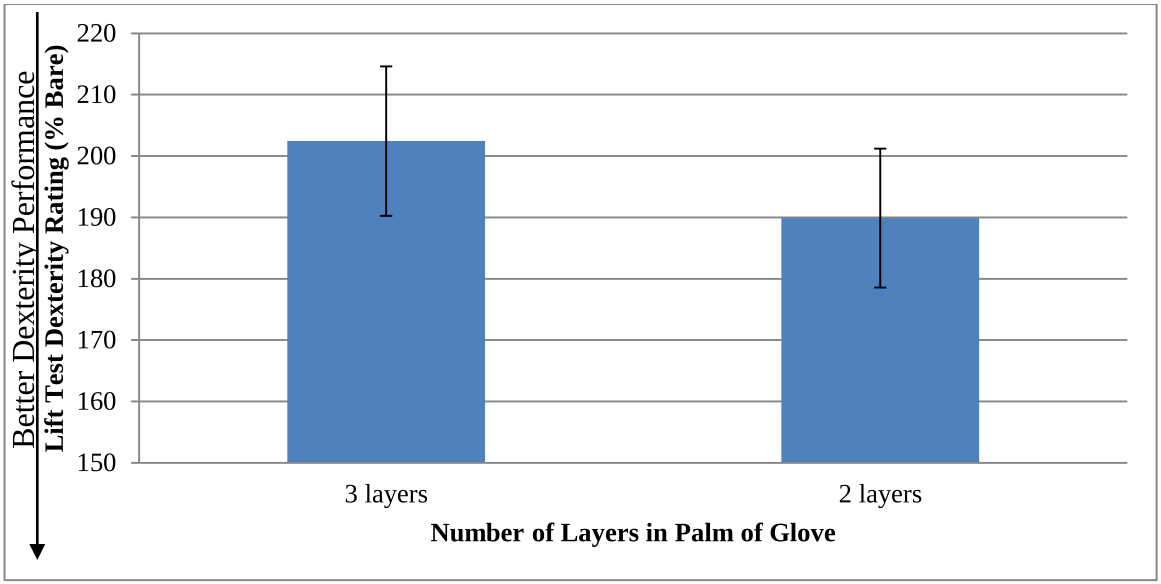
[11] Error bars show the standard deviation for each group mean.

[12] Connecting letters report is provided by collection of student's t-tests performed at the alpha=0.05 significance level. Moisture barrier types connected by the same letter are not significantly different.



t-Test, α = 0.05	3 Layers-2 Layers	t-Ratio= 2.011, Prob>t = 0.0302*

Figure 4.11 Effect of Palm Layers on Lift Test Dexterity[13]

4.3.2 Effect of Glove Construction on Performance in Tool Dexterity Test

Because the tool test involves a greater range of motion, whole hand movement and the extension of tool manipulations, it is not surprising that the NFPA 1971 compliant gloves rank differently, as compared to the lift test. The tool dexterity test provides a more complex measurement of dexterity that combines the fine dexterity and gross dexterity facets of glove hand function. It is affected by factors beyond the fingertip area, and therefore gives a different evaluation of the effect of outer shell and moisture barrier type.

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[13] Error bars show the standard deviation for each group mean.

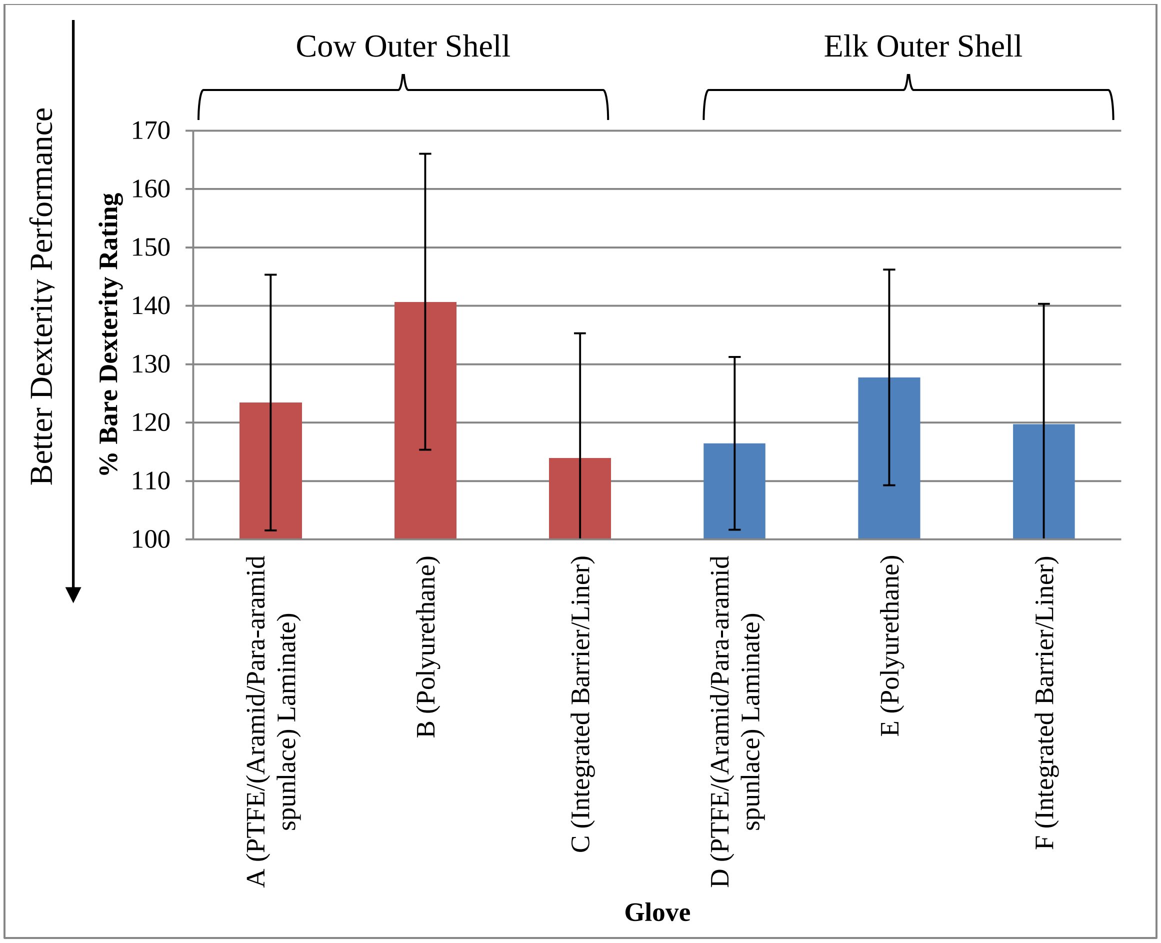

Figure 4.12 Dexterity Performance as Measured by the Tool Test (Gunn Cut Glove Designs)[14]

Figure 4.12 shows the effects of the moisture barrier component and type of outer shell leather on tool test glove dexterity. It compares six gloves with the same manufacturer having the same design construction but made with different moisture barriers. Moisture barrier effects were compared in gloves made with either cow or elk leather outer shells. The tool test indicates that the gloves with elk (the softer, more pliable leather shell) performed

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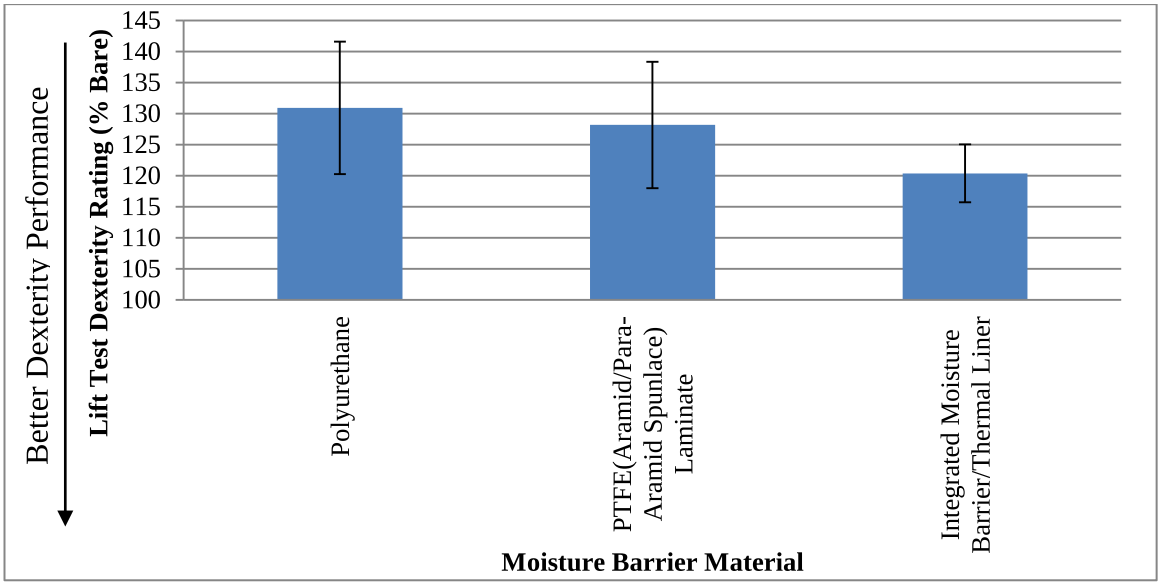
[14] Error bars represent the standard deviation ofdexterity ratings of five subjects.

better than their cow counterparts and the integrated moisture barrier/thermal liner was the best performer of the three moisture barriers. The tool test results further show that gloves made with PTFE(aramid-/para-aramid spunlace) laminate perform better than polyurethane barriers, a result opposite from the lift test. However, the effect of moisture barrier on tool test dexterity performance agrees with the effect of moisture barrier for the nineteen NFPA 1971 compliant gloves shown in Figure 4.13.



Level	2		B	B
	1	A	A	

Figure 4.13 Effect of Moisture Barrier on Tool Test Dexterity Performance

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[15] Connecting letters report is provided by collection of student's t-tests performed at the alpha=0.05 significance level. Moisture barrier types connected by the same letter are not significantly different.

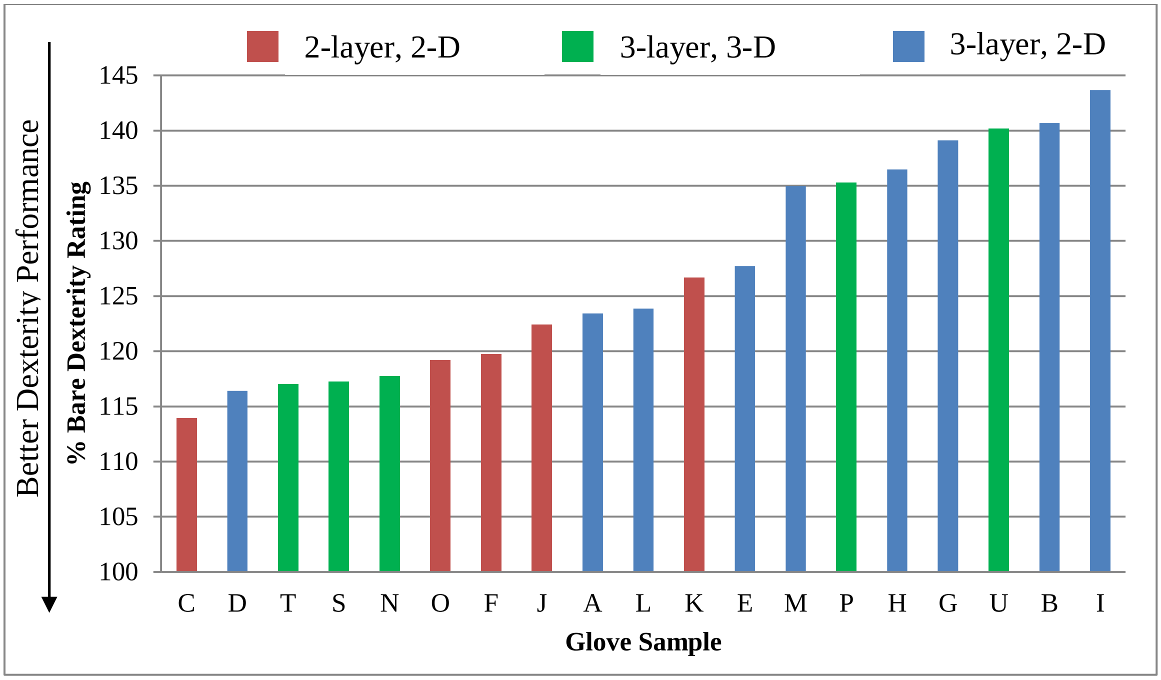

Figure 4.14 Tool Test Dexterity Performance of NFPA 1971 Compliant Gloves

Some 2-layer glove constructions do not perform as well in the tool test as in the lift test. Gloves K and J, while having some of the best lift test (fine) dexterity ratings, do not perform best in the tool test (combined fine and gross dexterity). For example, glove O, the best performing glove in the lift test is sixth as measured by the tool test, shown in Figure 4.14. When measured by the lift test, 3-D gloves T and S had mid-range dexterity performance as seen in Figure 4.8. However, when measured by the tool test, 3-D gloves N, T and S have three of the top five dexterity ratings shown in Figure 4.14. Three-dimensional gloves gloves N, T and S are constructed with the thinnest outer shell leathers in this study and have low composite weight as a result. Therefore, the tool test identifies not only gloves with fewer layers as being good performers, but also indicate the improvements in the dexterity performance of 3-D gloves occur as a result of thinner, more flexible outer shells, and lower palm composite weight.

4.4 Predicting Dexterity Performance Based on Materials Properties

Table 4.4 shows the correlation between palm composite thickness and dexterity performance in the incremental lift and tool tests. These data indicate that, glove stiffness, the coefficient of friction of the outer shell leather used in the palm of the glove, and palm thickness are poor single variable predictors of dexterity performance in either test.

Table 4.4 Single Predictors of Dexterity Performance

	Dexterity Test	
	Lift Test	Tool Test
Predictor	R^2	
Palm Composite Thickness	0.0045	0.0031
Glove Stiffness	0.0051	0.069
Palm Shell Static Coefficient of Friction	0.0062	0.0023

Furthermore, even though the shell materials have a range surface friction properties, this also has little effect on the ability to manipulate objects. These results suggest that the effects of material and construction on glove dexterity performance are complicated. They are not simply related to thickness, flexibility and surface properties of the materials used in glove construction.

4.5 Factors Affecting Incremental Lift Test Dexterity Performance

Figure 4.15, which includes both NFPA 1971 compliant gloves and also non-compliant gloves, shows that a strong relationship exists between lift test dexterity and measured glove bulk ($R^2 = 87\%$). In fact, glove bulk is the only factor that explains the variation in dexterity performance as a single variable predictor. As glove bulk increases, dexterity performance as measured by the lift test decreases. This finding shows a basis for firefighter complaints that associate glove bulkiness with decreased dexterity.

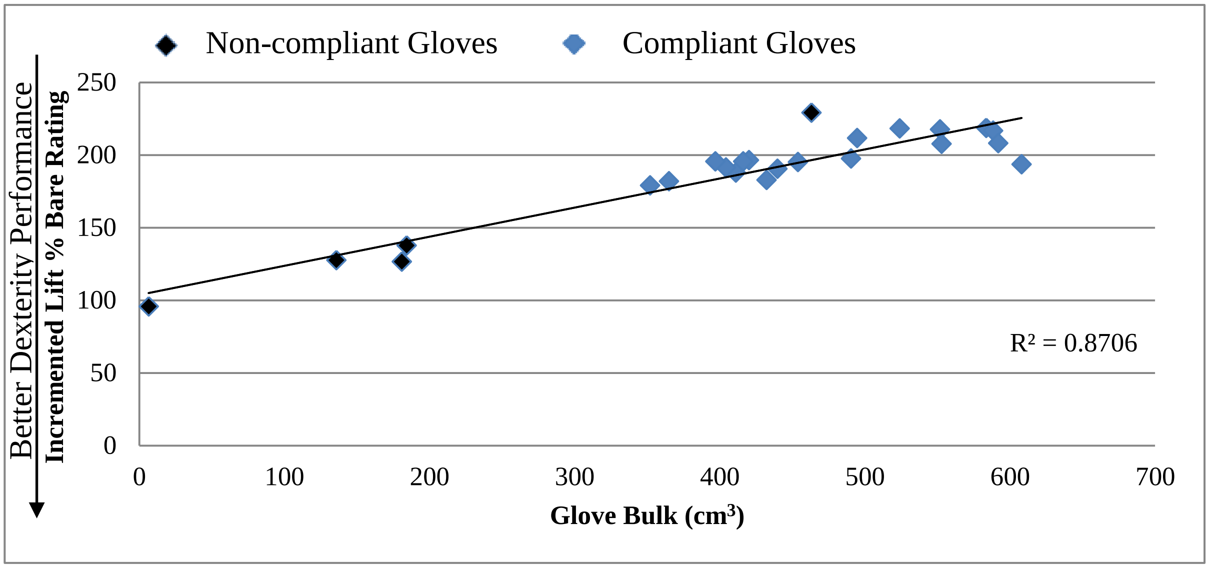

Figure 4.15 Glove Bulk (cm^3) vs. Lift Test Dexterity Rating (% Bare) (all 24 gloves)

Increased glove bulk is related to both glove materials and construction. Therefore, multiple regression models were developed to investigate these relationships. Only NFPA 1971 compliant gloves were included in the following multi-variable analyses. Table 4.5 summarizes the models related to lift test dexterity where an action is given for each predictor per model to increase glove dexterity performance.

Table 4.5 Incremental Lift Test Prediction Models

Model	R^2 Value	Response	Predictors	Sum of Squares[16]	Action for Better Performance
1	84%	Dexterity Performance	Glove Bulk	559	Decrease
			TL to MB Connection	652	None, Adhesive, or Tabs Sewn to Side
			Other Variables	476	---
2A	83%	Glove Bulk	Thumb Circumference	94,291	Decrease
			Palm Composite Thickness	36,108	Decrease
			Glove Stiffness	28,580	Decrease
			Other Variables	20,408	---
2B	46%	Glove Bulk	Thumb Type	373	Wing with a Seam or Wing
			Other Variables	615	---
3	37%	Thumb Circumference	Thumb Type	373	Wing with a Seam or Wing
			Other Variables	615	---
4	58%	Thumb Circumference	TL to MB Connection	568	None, Double-sided Tape and Sewn to MB
			Other Variables	419	---
5	67%	Glove Stiffness	Thumb Type	405	Wing or Wing with a Seam
			Back Shell Material	291	Synthetic, Kangaroo or Elk
			Other Variables	348	---

Model 1 is a forward selection stepwise regression model for lift test dexterity performance [22]. It shows how glove bulk and thermal liner to moisture barrier connection type can be used to explain the dexterity performance of NFPA 1971 compliant gloves.

Model 1

$$\begin{aligned} &Dexterity\ Performance = 160.65 \\ &+0.083 * Whole\ Glove\ Bulk(cm3) \\ &-7.36\ [TL\ to\ MB\ Connection\{Adhesive\ \&\ None\ \&\ Tabs\ sewn\ at\ side - \\ &Sewn\ to\ MB\ \&\ Double\ sided\ tape\}]\ . \end{aligned}$$

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[16] The Sum of Squares contribution for each model indicates how well each predictor explains the response when compared with the other predictors in the model. A predictor with a higher SS value than others suggests greater importance to that particular model.

This statistical model indicates that for gloves with the same thermal liner to moisture barrier connection, dexterity performance is reduced by glove bulk. Model 1 shows that, for gloves with similar bulk, gloves that have no thermal liner to moisture barrier connection, those connected using adhesive and those with tabs sewn to the side of the finger have better dexterity performance than those whose moisture barriers are sewn to the thermal liner or connected with double sided tape.

It is important to consider factors that influence thermal liner to moisture barrier connection type. For example, gloves with no thermal liner to moisture barrier connection are gloves that usean integrated, or single layer, moisture barrier/thermal liner. These gloves, therefore, have two layers in the palm composite instead of three. While number of palm layers is not significant enough to statistically describe dexterity on its own, it does affect connection type.

Table 4.6 Moisture Barrier/Connection Type Relationships

Connection Type	Integrated Moisture Barrier/Thermal Liner	Thin Polyurethane	Thick Polyurethane	PTFE(aramid/ Para-aramid Spunlace) Laminate
None	X			
Folded Rectangular Tab Sewn to Tip		X		
Sewn to Moisture Barrier			X	
Double-Sided Tape			X	X
Tabs Sewn at Side of Finger				X
Adhesive				X

The moisture barrier material may dictate connection methods. Table 4.6 shows that some connection types are very likely to be moisture barrier-specific. Gloves with an integrated moisture barrier/thermal line layer will obviously have no moisture barrier connection. Gloves with a thin, breathable polyurethane moisture barrier are the only gloves to employ the use of a folded rectangular tab sewn to the tip of the finger. These gloves also use a folded rectangular tab sewn to the tip to connect the moisture barrier to the shell as well. This results in two layers of tabs at the fingertip. Gloves with a thick, breathable polyurethane barrier are the only type to sew the thermal liner directly to the moisture barrier. However, gloves with thick polyurethane barriers and gloves with PTFE spunlace laminate barriers both use double sided tape. From this glove test group, in one case, a glove connects its PTFE spunlace laminate barrier to the thermal liner by attaching it with a tab sewn to the side of the finger. Gloves with a PTFE spunlace laminate barrier typically use adhesive to connect the barrier and thermal liner components.

4.5.1 Predictors of Glove Bulk

Regression analyses show that the following factors are significant predictors of glove bulk: palm composite thickness, thumb circumference and glove stiffness. Model 2A indicates that decreasing glove stiffness, palm composite thickness and thumb circumference reduces glove bulkiness.

Model 2A

$$\begin{aligned} Glove\ Bulk\ (cm3) = &\ -1345.4 \\ &+ 3.67 * Glove\ Stiffness(lb) \\ &+ 54.73 * Palm\ Composite\ Thickness(mm) \\ &+ 13.16 * Thumb\ Circumference(mm). \end{aligned}$$

Although there is a high correlation between glove bulk and glove stiffness, palm composite thickness and thumb circumference, correlation does not necessarily signify causality. That is to say, the action of reducing glove stiffness, or palm composite thickness or thumb circumference in and of itself will not necessarily decrease glove bulk. While related, these mechanical and dimensional properties are vastly complex and highly dependent on material and design properties.

Reduced glove bulk significantly impacts dexterity performance. Therefore, a second regression analysis was conducted that considered the effects of glove and design properties on bulk. Model 2B shows that thumb type also affects whole glove bulk. The average effect of wing and wing-with-seam thumb types are related to gloves who have lower glove bulk that those with a straight thumb.

Model 2B

$$Glove\ Bulk\ (cm3) = 486.5 - 55.05[Thumb\ Type\{Wing\ with\ Seam\ \&\ Wing - Straight\}]$$

The model shows that use of a wing thumb or wing-with-a-seam thumbs, as opposed to straight thumb designs, contribute to improved dexterity performance due to reduced glove bulk. Since thumb circumference is also a significant predictor of bulk in Model 2A (when glove stiffness and palm composite thickness are held constant), it is important to know how material selection and construction parameters affect thumb circumference. The three different levels of thumb types (wing, wing-with-a-seam, straight) were regressed against thumb circumference and resulted in prediction Model 3.

Model 3

$$\mathit{Thumb\ Circumference}\ (mm) = 98.13 + (\mathit{Thumb\ Type})\left\{\begin{matrix} \mathit{Straight}, 6.74 \\ \mathit{Wing}, 0.91 \\ \mathit{Wing\ with\ Seam}, -7.65 \end{matrix}\right\}$$

Model 3, predicting 37% of variation within thumb circumference with only thumb type, shows that a wing-with-a-seam thumb design results in a lower thumb circumference in comparison to wing and straight thumb designs. Wing thumb constructions have a smaller thumb circumference than straight thumbs. In light of the positive correlation between thumb circumference and glove bulk and dexterity, it is apparent that a wing, or wing-with-a-seam thumb design improves dexterity performance.

Model 1 predicts lift test dexterity using two factors: glove bulk and thermal liner to moisture barrier connection. Since liner connection types are in the fingertips, the effect of connection type on thumb circumference (a good predictor of bulk in Model 2A) was examined. A significant linear combination was developed that compares the average effect of three types of connections (folded rectangular tabs sewn to tip, tabs sewn at side, adhesive) to the average effect of the remaining three types of thermal liner to moisture barrier connections (sewn to moisture barrier, none, double-sided tape). Factors affecting thumb circumference are shown in Model 4.

Model 4

$$\begin{aligned} &\mathit{Thumb\ Circumference}\ (mm) \\ &\qquad = 99.11 \\ &\qquad - 5.67\ [\mathit{TL\ to\ MB\ Connection}\{\mathit{Folded\ Rectangular\ Tab\ Sewn\ to\ Tip} \\ &\text{"}\&\ \mathit{Tabs\ sewn\ at\ side}\ \&\ \mathit{Adhesive} - \mathit{Sewn\ to\ MB}\ \&\ \mathit{None}\ \&\ \mathit{Double\ Sided\ Tape}\}]\text{"} \end{aligned}$$

This model indicates that, folded rectangular tabs sewn to tip, tabs sewn at side, and adhesive connection types add more to a glove's thumb circumference than do sewn to moisture barrier, double-sided tape or no connection types. Considering the effect of connection type on dexterity and the effect of thumb circumference on bulk, a glove with no connection, one sewn to the moisture barrier or double-sided tape connecting the thermal liner to the moisture barrier would have a thumb with a smaller circumference, less bulk, and better dexterity performance.

4.5.1.1 Relationship Between Glove Bulk and Measured Stiffness

Factors that affect whole glove stiffness are shown by the following regression model:

Model 5

$$\begin{aligned}&Glove\ Stiffness\ (lb) = 65.41\\&-4.05[Back\ Shell\{Synthetic\ \&\ Kangaroo\ \&\ Elk - Cow\}\\&+(Thumb\ Type)\begin{Bmatrix}Straight, 6.36\\ Wing, -3.48\\ Wing\ with\ Seam, -2.89\end{Bmatrix}\end{aligned}$$

This model shows that gloves with straight thumb designs are generally stiffer than gloves made with wing or wing-with-a-seam thumb designs. It also indicates that gloves made with a kangaroo, elk or synthetic knit back shell materials are less stiff than those made with a cow leather back shells. However, glove stiffness is not solely related to the thickness of the shell material, for elk is the thickest leather examined in this study. Furthermore, there is a relationship between the measured shearability of the outer shell and glove stiffness, irrespective of thickness. Figure 4.16 shows that gloves with elk leather, and synthetic knit back shells have lower shear resistance than gloves made with cow leather outer shells.

Model 5 also shows that gloves made with a kangaroo leather back shells are more flexible than gloves that use cow leather in the back of the glove. This may be because kangaroo leather is thinner than cow leather.

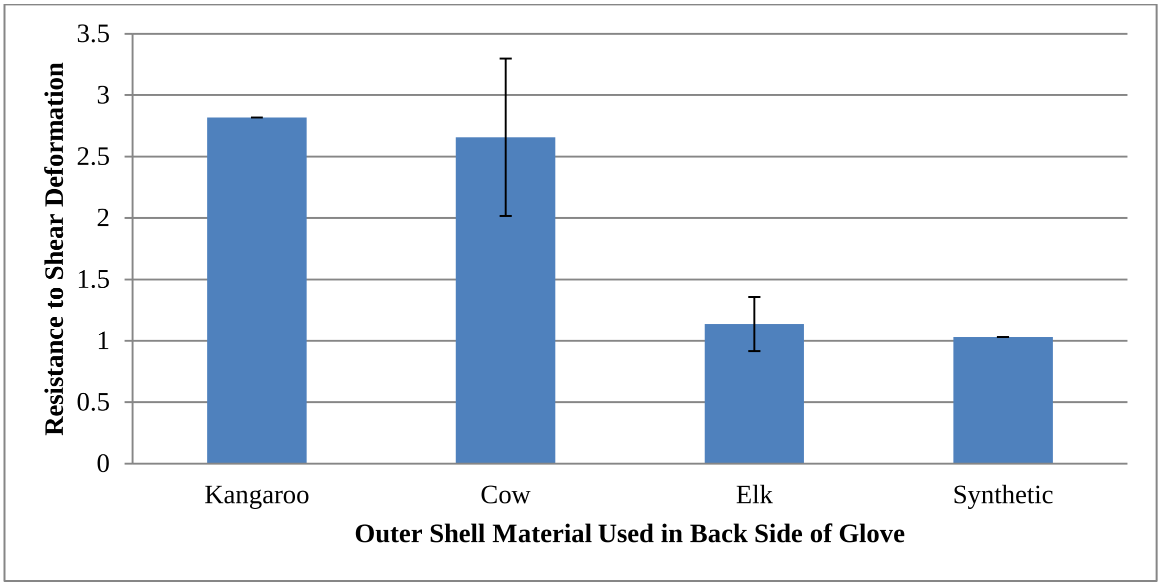

Figure 4.16 Resistance to Shearing by Back Shell Material[17]

4.5.1.2 Relationship Between Palm Composite Thickness and Glove Bulk

One of the predictors of the glove bulk measurement in Model 2A is palm composite thickness. However, it should be noted that palm composite thickness is a poor single variable predictor of bulk as seen in Table 4.4. It can be assumed to increase bulk only when other design features are held constant such as glove stiffness and thumb circumference. Palm composite thickness only indicates the thickness of the layers of material used in the glove construction and is, therefore, a poor single variable predictor of glove bulk. Glove

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[17] Error bars show the standard deviation for each group mean.

bulk is also influeced by the uncompressed whole glove thickness, both materials and airspaces. Consequently, many design features besides thickness alone predict glove bulk.

4.6 Factors Affecting Tool Test Dexterity Performance

While lift test dexterity correlates well with glove bulkiness, this is not the case for tool test dexterity. Figure 4.17, shows only a moderate positive trend between tool test dexterity and glove bulk. This finding indicates that other material and construction factors are affecting this dexterity measurement.

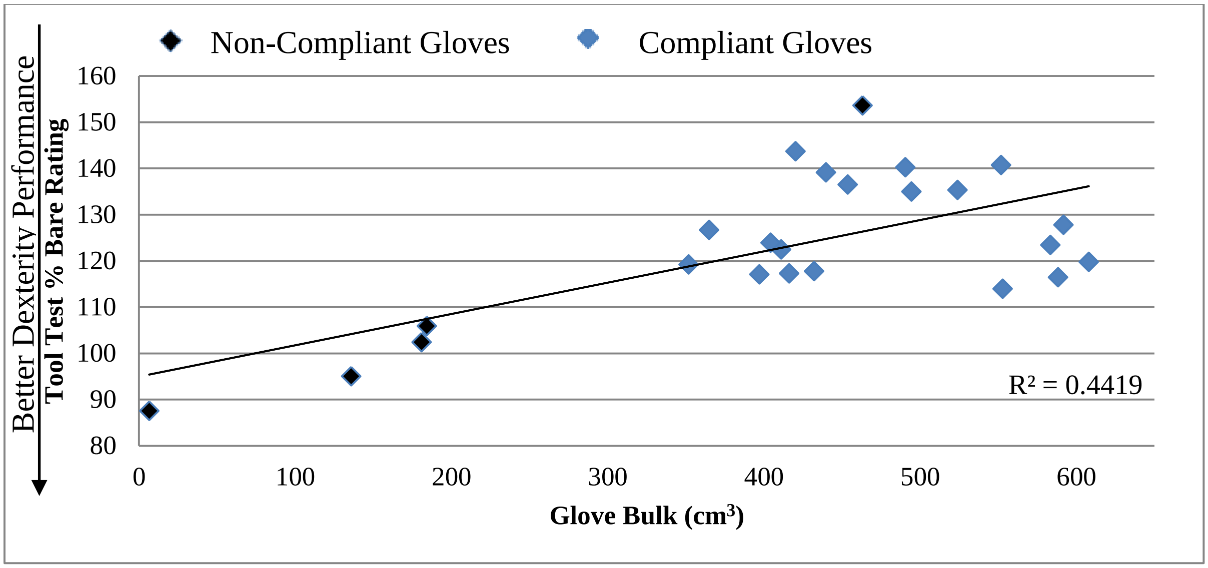

Figure 4.17 Glove Bulk (cm^3) vs. Tool Test Dexterity Rating (all gloves)

Table 4.7 summarizes models that predict tool test dexterity performance based on gloves stiffness and construction factors.

Table 4.7 Tool Test Prediction Models

Model	R^2 Value	Response	Predictors	Action for Better Performance
Partition	82.1%	Dexterity Performance	Palm Composite Weight	Decrease
			Whole Glove Stiffness	Decrease
6	88.9%	Dexterity Performance	Thumb Circumference	Increase
			Back Shell Material	Kangaroo or Elk
			Moisture Barrier Material	Breathable, thin Polyurethane or Integrated Moisture Barrier and Thermal Liner

A partition model, shown in Figure 4.18, was developed using the data from the NFPA 1971 compliant gloves to determine which variables affect tool test dexterity. Each property variable was considered and the highest reduction in total sum of squares determined the optimum split at each step. This model revealed that palm composite weight and measured glove stiffness are the most influential factors determining tool test dexterity performance.

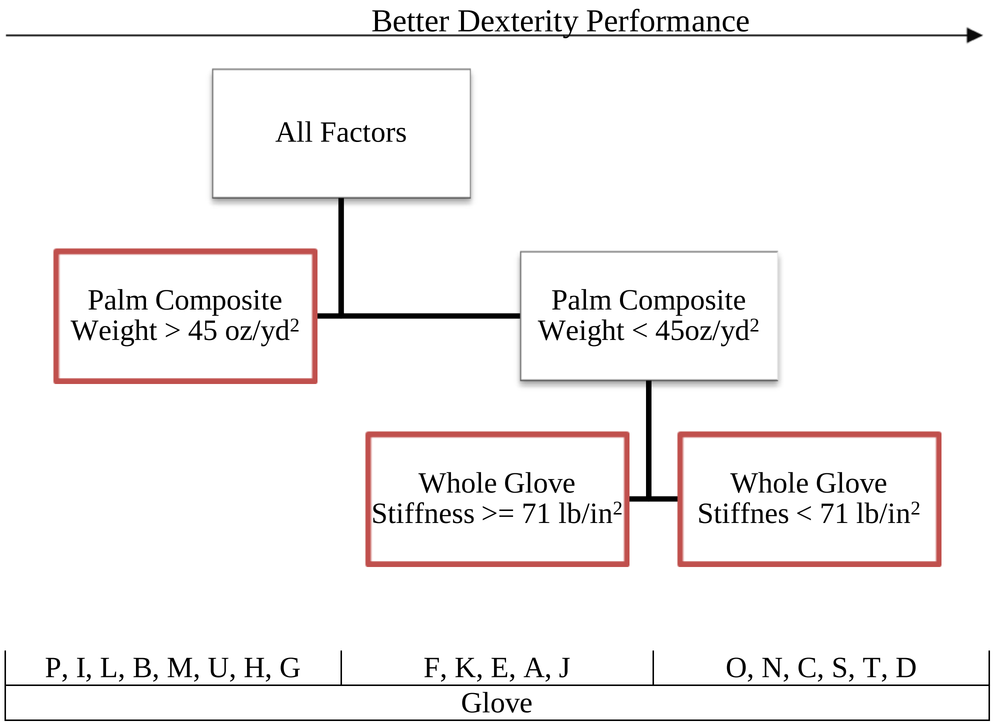

Figure 4.18 Partition Model of Dexterity as Measured by the Tool Test (19 NFPA 1971 Compliant Gloves)

The two splits that separate the gloves into three levels of dexterity performance explain 82% of the variation in the dexterity ratings among the gloves in the tool test. Figure 4.18 shows that gloves with a palm composite weight greater than 45 oz/yd^2 have poorer dexterity performance than those gloves with a palm composite weight of less than 45 oz/yd^2. Of the gloves with a lower composite weight, another difference in dexterity performance was detected; one based on glove stiffness. Gloves whose stiffness was less than 71 lb-f/in^2 had better dexterity performance than those whose stiffness was greater than 71 lb-f/in^2. The effect on dexterity of glove stiffness was previously outlined in the discussion on the lift test and while this gives us a good picture of how measured variables can be used to predict dexterity performance, it does little to help with the design process. There is a need to know how to decrease palm composite weight and glove stiffness by design and material selection.

When regression analysis was performed on tool test dexterity data, a model explaining 88.9% of the variation was created by the selection of significant variables including thumb circumference, back shell material and moisture barrier material. The effect on dexterity performance is shown in the prediction equation in Model 6:

Model 6

$$
\begin{aligned}
&Dexterity\ Performance = 199.9\\
&-0.77 * Thumb\ Circumference\ (mm)\\
&-3.38[Back\ Shell]\{Kangaroo\ \&\ Elk - Cow\}\\
&+[Moisture\ Barrier]\left\{\begin{matrix} Thick\ polyurethane, 15.85\\ PTFE\ Spunlace\ Laminate, 3.30\\ Integrated\ MB/TL\ A, -0.12\\ Integrated\ MB/TL\ B, -5.54\\ Thin\ Polyurethane, -13.49 \end{matrix}\right\}
\end{aligned}
$$

The back shell material had an effect on dexterity performance, with the softer, more pliable kangaroo and elk leathers performing better than cow leathers. The moisture barrier contribution indicates only that the thick polyurethane barriers perform worse than the thinner polyurethane barriers. Bordering on the significance level, the integrated moisture barrier/thermal liner B performs better than the integrated moisture barrier/thermal liner A while integrated moisture barrier/thermal liner A is better than PTFE spunlace laminate barriers.

As thumb circumference increases (while back shell material and barrier material are controlled), dexterity performance improves. While the lift test predicts that a smaller thumb circumference improves dexterity performance, the tool test predicts that a larger thumb circumference improves dexterity performance.

One of the best performing NFPA 1971 compliant gloves (Glove D) had the largest thumb circumference and one of the worst performing compliant gloves (Glove U) had the smallest thumb circumference (Figure 4.19). But also, one of the best performing compliant gloves (Glove T) had a small thumb circumference as well. This anomaly illustrates that a larger or smaller thumb circumference does not necessarily guarantee a glove with better or worse dexterity performance.

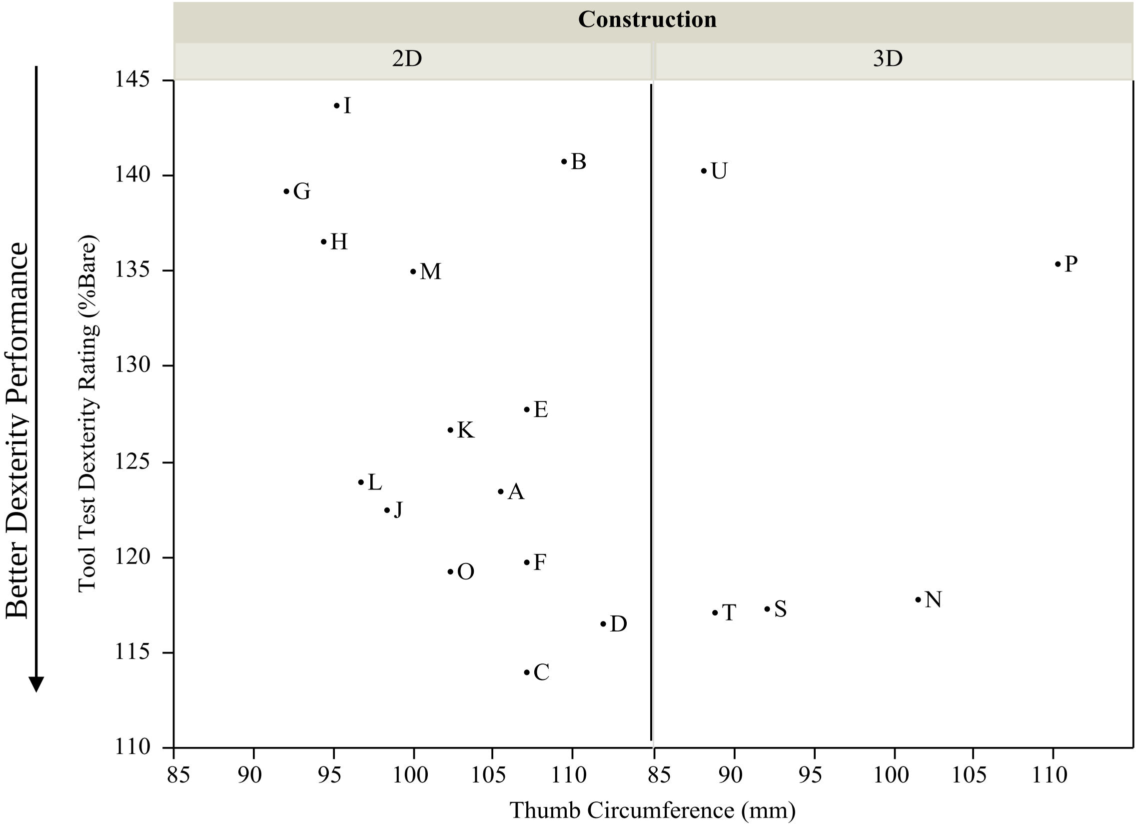

Figure 4.19 Effect of Thumb Circumference and Construction on Tool Test Dexterity

There are differences in the effect of thumb circumference on dexterity performance for 3-D and 2-D gloves. For 2-D designs, as thumb circumference increases, dexterity performance increases as seen in Figure 4.19. Because Glove D has a larger thumb circumference, the expectation would be that it would perform worse because of the "extra" material. However, the thumb design is 2-D, effectively a 3-layer palm composite and a 3-layer back composite sewn together. This design drives the seams that connect the two sides away from the thumb, effectively allowing the wearer to push the material out of the way so that the encumbrance to performing a task lies mainly with the thickness and compressibility of the palm composite localized at the fingertip.

The relationship between thumb circumference and dexterity for 3-D gloves is less clear as indicated by these data. Compliant gloves S, T and N are all 3-D gloves, with S and T having small thumb circumferences and glove N having a midrange thumb circumference. While these gloves perform well in the tool test, glove U, a 3-D glove with the smallest thumb circumference performed third worst. The between-the-fingers fourchette piece, signature to 3-D designs, adds two more seams to the finger construction, in many cases drawing those seams closer to the fingertip so that the encumbrance to the task involves overcoming seam thickness where composite thickness may have been doubled. In cases such as these, it is easier to minimize this "doubling" problem by choosing more compressible composites. Gloves T, N and S have the thinnest outer shell leathers as illustrated in Figure 4.20 (but not the thinnest composites).

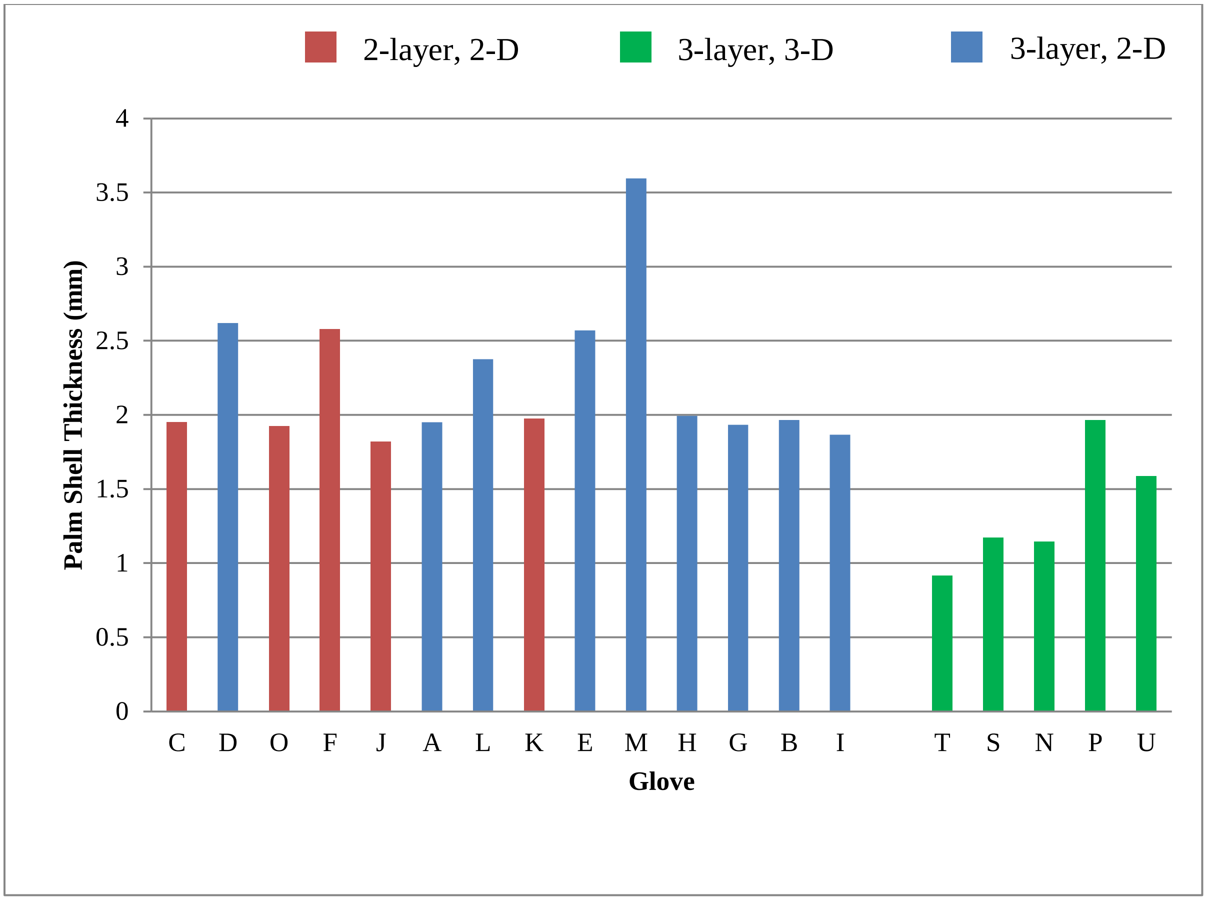

Figure 4.20 Palm Shell Thickness and Construction

These gloves (N, T, S) also have three of the four lowest palm composite weights, shown in Figure 4.21, meaning that there is more airspace per thickness of composite and, therefore, more compressibility.

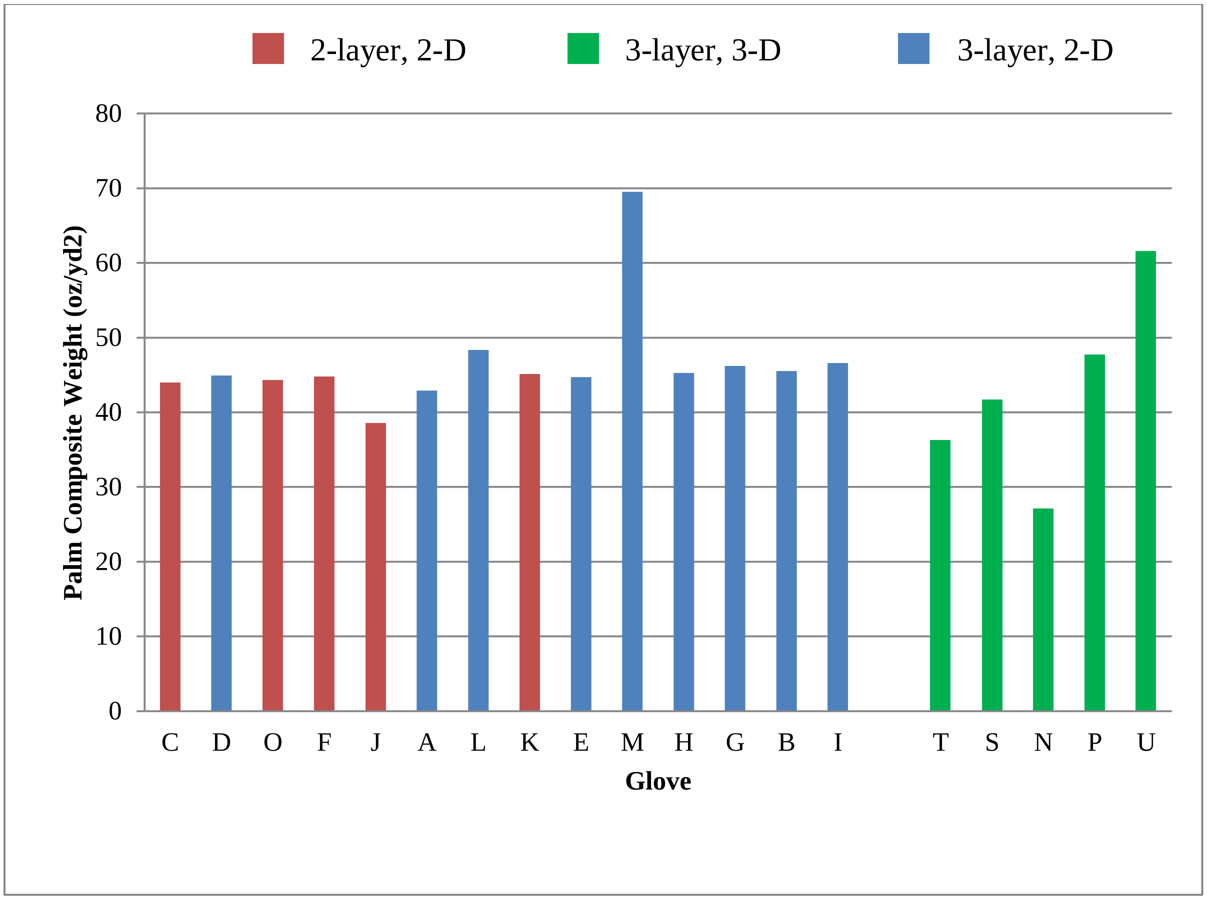

Figure 4.21 Palm Composite Weight and Construction

The answer to the thumb circumference conundrum lies with how close the glove design allows the wearer's finger to get to the object. This can be more influenced by seam placement, composite compressibility and flexibility, than by the size of the glove fingertips.

Chapter 5. Dexterity Study Conclusions

This phase of the research demonstrated dexterity test methods that provide improvements over the pegboard method currently called for by the NFPA 1971 standard. The incremental lift and the tool tests are less variable, and provide better discrimination between structural firefighting glove dexterity performances than do the pegboard test methods. The lift test measures fine, or fingertip, dexterity. The tool test measures both fine and gross, or whole glove, dexterity. The tool test provides a job-relevant prediction of glove dexterity.

Statistical models were used to determine correlations between glove construction, materials and dexterity performance. The thickness of the layered composite used in the glove is shown to be a poor predictor of dexterity performance in either the tool or lift test. Most properties, when considered alone, do very little to predict dexterity performance. The palm shell material of most structural firefighting gloves is leather and the surface properties among these leathers did not have a significant effect on dexterity performance. Other shell material properties, however, did affect dexterity performance. Both the lift test and the tool test show that gloves with kangaroo and elk leathers or synthetic knit back shell materials provide better dexterity than gloves with a cow back shell material. This is because kangaroo, elk and synthetic materials, regardless of material thickness, have a low resistance to shear forces and bend and deform easily.

Measured glove bulk provides the best single variable prediction of fine dexterity performance. As glove bulk increases, fine dexterity performance, as measured by the lift test, is diminished. Many factors affect glove bulk, including thumb type and circumference, as well as glove stiffness. Both the lift test and the tool test indicate that wing or wing-with-seam thumb constructions decrease bulk and glove stiffness, and therefore, improve glove dexterity. For a 2-layer or 3-layer glove and a 2-D or a 3-D constructions, the insert connection types and the thumb type affects dexterity performance.

The lift test and the tool test rank compliant structural gloves differently. Because the lift test measures fine dexterity, gloves that have good fingertip designs, including 2-layer 2-D gloves (O, K, J) and also gloves that have compressible palm composites (N), perform best in this test.

Because the tool test measures the dexterity of the entire glove, 3-D glove designs may perform better than indicated by the lift test. Glove C is the best performing compliant glove in the tool test. This glove uses an integrated moisture barrier/thermal liner layer in a 2-layer design. Other gloves that perform well, (T, S, N), are 3-D gloves made using thinner, more pliable outer shell leathers. Glove O, which performs well in this test, is a 2-layer glove that incorporates a pliable knit outer shell in the back side of the glove. Although, by itself, moisture barrier does not determine dexterity performance, gloves constructions that incorporate thick polyurethanes and PTFE(aramid/para-aramid spunlace) laminate moisture do perform poorly in both lift and tool test measures of glove dexterity.

Chapter 6. Gloved Grip Study

6.1 Introduction

How an object is held or grasped and the resulting interface between hand and glove determine the “grip” performance of a glove in any sort of task, whether pushing, pulling, holding or torque motions. Because there are many possible orientations when grasping an object with the hand, frictional, directional force, contact area and glove properties can influence grasp strength. One type of grasping action, known as precision grip, refers to grasping an object between the distal pads of the forefinger and the thumb. Pincer grip is a different grasping action in that the object is held between the distal pads of the thumb and the distal pads of all four fingers [23].

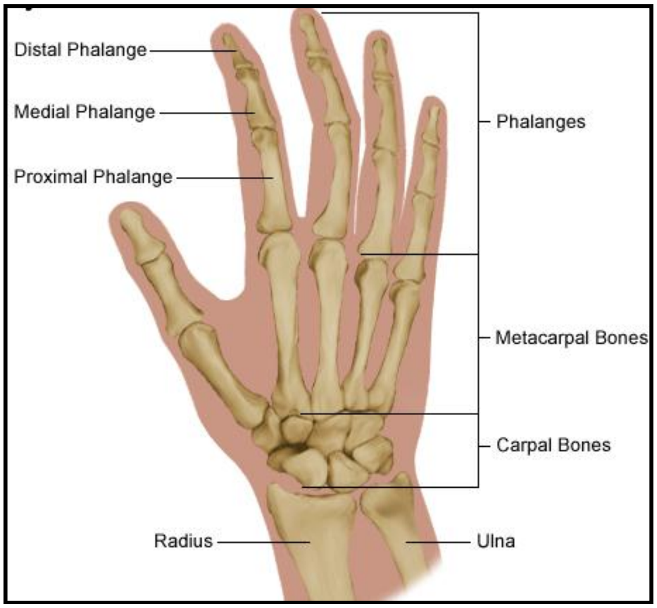

Figure 6.1 Parts of the Fingers and Hand [24]

Figure 6.1 identifies the parts of the hand involved in gripping actions. As shown in Figure 6.2, the power grip is a grasp orientation commonly performed by firefighters. The power grip describes how the fingers (and many times palm) clamp down around an object, while the thumb makes a counter pressure. The combined forces that allow the hand to hold objects is referred to as a grasping force.

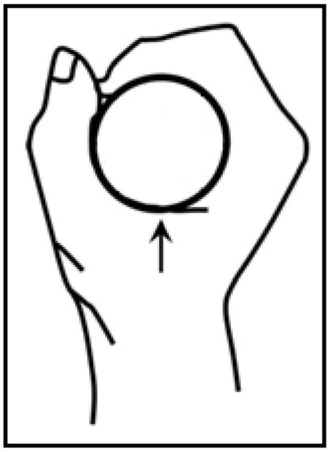

Figure 6.2 Power Grip [25]

The term grasp force is interchangeable with the normal force acting on the object being grasped by the hand and fingers. This is often equated with good “grip” because this grasp force (normal force) is the basis for countering disruptive forces to the interface between the hand and the grasped object. Optimizing this normal force in power grip position is the key to overcoming all types of disruptive or counter forces.

In cases like turning a doorknob, grip force (normal force) is applied to an object to produce torque to prevent the object from rotating in the hand. These torque forces are related to the shear force and also the moment arm about the axis [26]. There are other cases where grip force (normal force) is applied to produce thrust (or shear) forces to prevent objects from sliding out of the hand. Maximum generated shear force is related to the normal (grasp) force and the static coefficient of friction at a given point of contact between the hand and the gripped object [26]. Therefore, overcoming induced shear forces involves increasing the number of contact points between the hand and the gripped object. This increases the effect of frictional force and its relationship to normal (grasp) force. So to improve resistance to disruptive forces, it is important to increase contact points, static coefficient of friction and normal force (grasp force) to the gripped object.

6.1.1 Contact Area and Handle Diameter

Applied normal force is positively related to the contact area between the hand and the grasped object; as contact area increases, more normal/grasp force can be transferred to the grasped object.

Many tools used by firefighters, such as pike-poles and axes generally have cylindrically-shaped handles. Maximum grip/grasp force is dependent on cylinder handle diameter, and certain diameters have been found to maximize grasp strength. Handles with diameters that are too small reduce the contact area between the handle and the fingers because finger flexion creates folds in the skin [26]. Handles with diameters that are too large can also cause a decrement in contact area and gripping force. When the handle is gripped, the interphalangeal joint rotates toward the handle, and force is concentrated on the fingertips which causes the medial and proximal phalanges to lift away from the handle [26]. In addition, the fingers are more open which causes the moment arms for finger flexor muscles to decrease. This causes a reduction in grip/normal force applied to the handle. Figure 6.3 shows these phenomena.

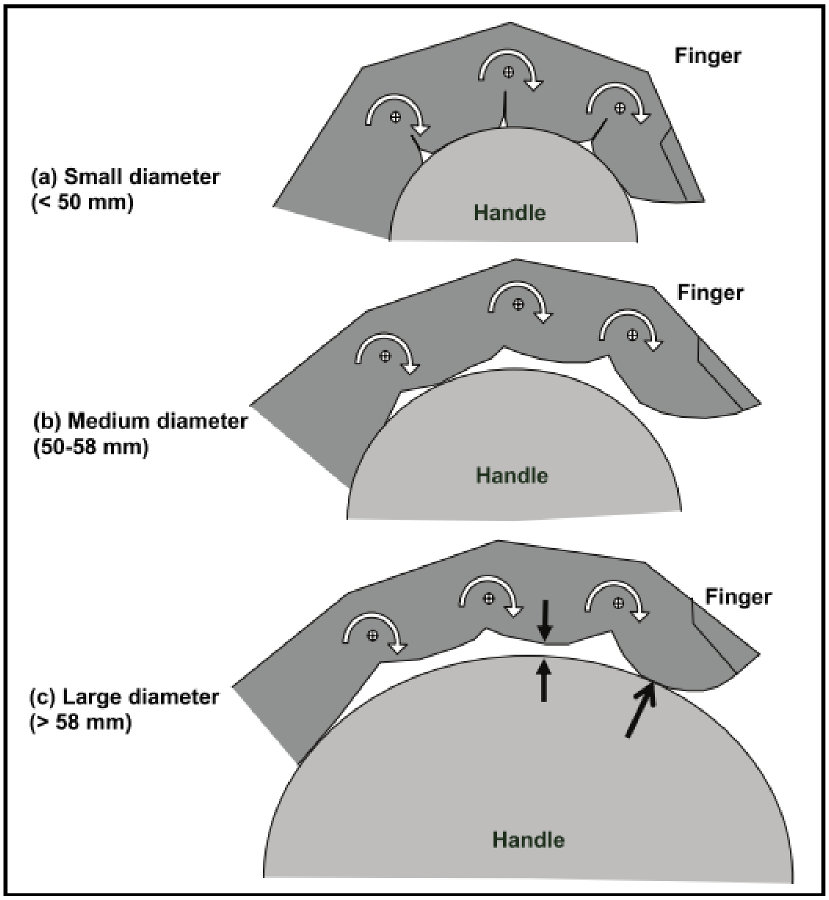

Figure 6.3 Handle Diameter Size Effect on Finger Placement [26]

In a barehand grip study, Seo found that this optimal cylindrical diameter was between 50 mm and 58 mm [26]. Kong used a force-glove system in his study determining optimal handle diameter for maximizing grasp strength. Since the force-glove system increased the resultant diameter of the handle with the addition of its own thickness, Kong determined, 40 mm, 45 mm and 35 mm were the most comfortable handle diameters for maximum exertion [25].

6.1.2 Force Distribution

The mechanisms behind discovering an optimal handle diameter primarily relate to resultant force distributions of the hand on the grasped object. Figure 6.4 shows the effect of handle diameter on the normal/grip forces generated by differing parts of the hand. Because of the finger positioning, the handle diameter of 45.1 mm allowed the combined normal forces of the thumb and fingers to react together in opposition to the normal force generated by the palm [27]. This handle with diameter 45.1 mm allows for better resultant grasp force than the handles with 57.8 mm and 83.2 mm diameters. Much larger handles, like the 83.2 mm diameter handle in Figure 6.4 dictate the finger positioning in such a way that the fingertip force and thumb force act against each other. This results in little reaction force on the palm, and thus, a lower grasp force.

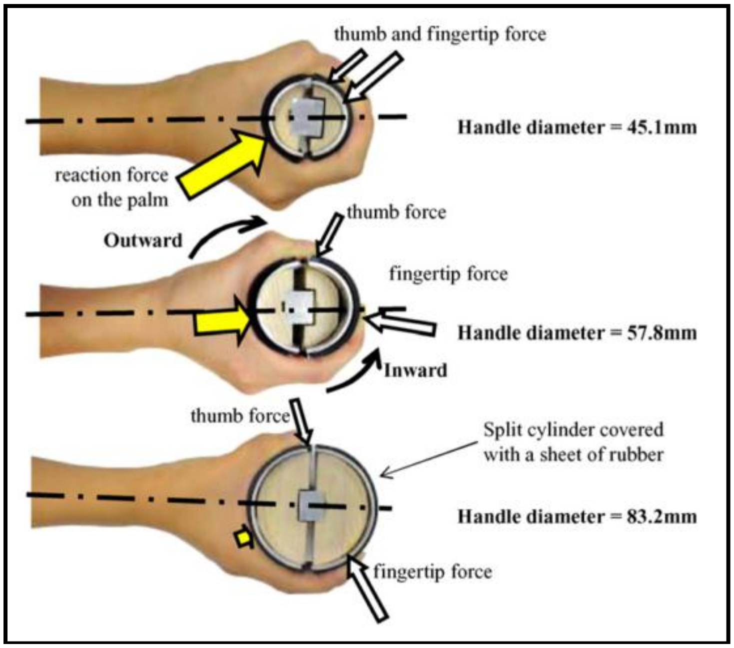

Figure 6.4 Force Reactions on Varying Handle Diameters [27]

Differences in the effect of gloves on torque strength have arisen between studies likely due to the direction of torque application by the hand, the orientation of the handle to be twisted, the decision of whether or not to include the use of hand tools and the diameter of the handles, [25; 28; 29; 30]. Not only does the diameter of the handle affect the force distribution, but the direction of torque exertion around the long axis of a handle affects the maximum grip/normal force and force distributions. The normal force acting on a handle was 22% greater when twisting in the direction the fingertips points than in the direction the thumb points [27].

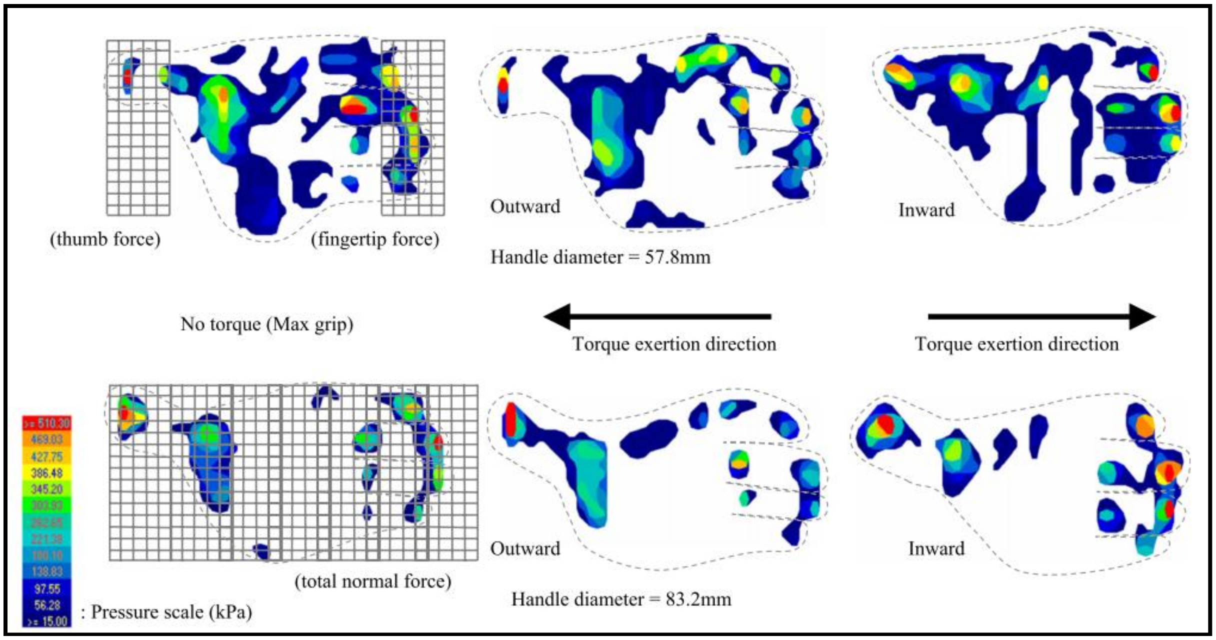

Figure 6.5 Force Distribution for Inward and Outward Torque Exertion Directions by Handle Diameter [27]

Figure 6.5 shows how higher normal forces are generated by the fingertips when the direction of torque exertion is toward the fingertips. The figure also shows how as the handle diameter increases, the palm contributes much less to the total normal force acting on the handle [27]. Work by Kong support this study and showed that the middle finger and also the distal phalangeal segment of each finger produced the largest forces for all handle diameters [25].

6.1.3 Contact Area and Friction

In order to counter disruptive forces like external torque and thrust forces, the grasp action creates friction. Because greater contact area between glove/hand and gripped object is associated with a higher coefficient of friction and thus better grasp force, the glove/object interface becomes even more important [26; 31]. Glove design attributes like fit can help to raise the effect of friction between the glove and grasped object and also between the hand and the inside of the glove [31]. The influence of the frictional surface properties of gloves on grip performance varies from study to study. Although it can be hard to separate frictional properties from whole glove or material thickness properties, Groth attempted such a feat by coating the bare hand and a pair of single-layer leather gloves with multiple additives to achieve similar coefficients of friction on both surfaces. Although there was no consistent relationship between the transport speed of an aluminum cylinder and coefficient of friction, when coefficient of friction was extremely low, the total number of transports within three minutes was significantly lower, [32].

6.2 Effect of Gloves on Grip

Structural firefighting gloves require a level of protection that often results in decreased grip performance. Buhman, among others, suggested that reduced tactile sensitivity caused by a donned glove could cause this decrement in grip strength because of reduced tactile feedback [33]. Much of this reduced sensitivity can be attributed to increased glove thickness associated many times with increased protection. Cochran, demonstrated that even a thin cotton glove can reduce grasp strength by as much at 7.3% of the barehand performance [33].

Human effort or exertion when gripping an object is not likely diminished by the use of gloves, but some of the hand effort is, however, absorbed by the glove. The effort it takes to bend, compress and stretch a glove to the shape of the gripped object is absorbed by the glove, leaving less hand energy effort as resultant normal force to grasp the object [31]. For this reason, the grip strength of a bare hand is usually higher than that of a gloved hand [5; 34]. Decreasing glove bending, compression and stretching resistances is likely to improve the gripping strength of a gloved hand. Stiffness related to the glove design and materials generally increases with the thickness of the glove material. Therefore, reducing the stiffness and thickness of these materials will likely decrease the effect of a glove on strength reduction. Increasing glove material thickness decreases grip performance, and also generally decreases the area of contact with the gripped object. As previously mentioned, this can have a detrimental effect on grip performance. Muralidhar discovered, through selective layering in the palm region, that minimizing the glove thickness along the palm creases had a higher affect on maximizing grasp performance than reducing thickness alone [5].

Various studies have shown that an optimum handle diameter exists so that the distributed grip pressure is maximized, but many of these studies have discovered this diameter using a bare hand. The thickness of a donned glove on the palm side can directly increase the effective handle diameter. Therefore, it is likely that minimizing glove palm thickness will decrease the glove effect on grasp strength reduction.

Fatigue is a factor in any extended grasping action where firefighters may not generate enough grasp/normal force to overcome external torque or thrust forces. In such cases, the grasped object will slip from the hand. Firefighters have been known to tire more quickly when transferring grip effort to stiffer firefighter gloves. In addition, gloves that fit the hand closely provide less resistance to grasp strength [5; 28].

6.3 Grip Study Objectives

The objectives of the grip study were to:

- Compare different glove grip test methods for assessing the grip performance of a selected group of structural firefighting gloves.
    - Demonstrate improved, more job-relevant test methods for characterizing structural firefighting glove grip functionality.
    - Develop new grip test methods that can be used to differentiate between structural firefighting gloves based on their grip performance.

These grip test methods were used to study the effect of glove materials, constructions and designs on grip performance in order to:

- Develop statistical models that predict a glove's grip performance from glove material and design properties.
- Recommend structural firefighting glove designs for improved grip performance.

6.4 NFPA 1971Tests for Glove Grip Performance

The first the NFPA 1971 structural firefighting glove grip performance requirement was introduced in 1997 in the form of three separate grip tests, [12; 14]. These tests involved measuring the maximum voluntary exertion before slippage on a horizontally oriented rope attached to a force gauge. Dry and wet-conditioned gloves were tested on a dry rope and also wet conditioned gloves were tested on a wet-conditioned rope. The NFPA 1971 standard applied this test to evaluate the grip performance of gloves by comparing a subject's bare-handed test performance to his gloved test performance using the following equation:

$$\% \, of \, barehand \, control = \frac{Pulling \, Force \, (with \, gloves)}{Barehand \, Pulling \, Force \, (without \, gloves)} \times 100$$

In the 2007 version of the NFPA 1971 standard, the grip performance test was reduced to include only wet-conditioned gloves on a wet-conditioned rope because this was considered the worst-case scenario [11].

6.5 Limitations and Drawbacks of the Current Glove Grip Test Method

The grip test in the current version of the NFPA 1971:2007 standard has many limitations associated with its implementation and interpretation. Extensive training and communication among third party testing groups has been necessary in an attempt to control for posture, body weight, pulling rate and initial pulling force, each of which, if not controlled, can have major sway upon maximum force output generated.

The limitations of the current grip performance evaluation test do not lie only with method consistency and repeatability, but also with issues of safety. Since the method of measurement records only the maximum force generated by a gloved hand before slippage, the current grip performance method does not measure catastrophic grip failure characterized by a complete separation of the glove surface from the grasped surface and hence a slippage and a regrip.

Chapter 7. Grip Study Experimental Procedures

This research used current, enhanced and newly developed grip performance test methods to characterize a selected group of structural firefighting gloves. The same twenty-four gloves used in the dexterity study were used in the grip study. Material level, whole glove, and glove design properties were used to characterize the combined effect of these factors on grip performance. An objective was to determine the optimal grip performance test method for characterizing structural firefighting gloves. These tests were used to examine the effect of the glove, materials properties and design characteristics on measured grip performance.

7.1 Glove Grip Tests

Seven different grip tests were performed on the group of test gloves described in Table 3.1. The group order and glove order within each group were randomized for each subject for each test. The wet tests were conducted after all the dry tests were completed. The grip rating for each glove for each test was determined by comparing the maximum gloved grip force to the barehand grip force for each subject averaging over three repetitions. For both dry and wet tests, the percent of barehand control was calculated by comparing to the dry barehand condition only.

7.1.1 Wet Conditioning

Gloves: Glove pairs were wet conditioned by first being donned by the subject, then fully submerged into two containers of water at a temperature of 21°C, ±3°C (70°F, ±5°F) for 2 mins +12/-0 sec. The gloves were then removed from the hand and hung vertically by digit 5 with the glove opening facing down for 2 mins +/-12 sec. [35].

Rope: The 10 mm, (3/8 in) diameter three strand prestretched polyester rope, specified in NFPA 1971 was wet conditioned by immersion in water at a temperature of 21°C, ±3°C (70°F, ±5°F) for 2 minutes and then dripped dry for 5 minutes between glove specimens [16].

Poles: Poles used during the wet vertical pull tests and during the wet torque test were wiped with a saturated wet cloth (21°C, ±3°C (70°F, ±5°F) before each repetition.

7.1.2 Horizontal Wet Rope Pull: Fixed Stance

The twenty-four glove pair specimens were tested for grip performance according to NFPA 1971 Section 8.39 which specifies three successive horizontal pulls on a wet-conditioned rope with wet-conditioned gloves [16]. The NFPA 1971 standard specifies that the human test participant, with feet firmly planted, shall grasp the rope with both hands, one in front of the other without the thumbs overlapping the fingers. For consistency a stance apparatus, shown in Figure 7.1, was employed so that subjects would stand facing the rope, with feet shoulder width apart and so that he/she would not fall forward during the pull.

Figure 7.1 Horizontal Rope Pull (Fixed Stance)

The grip rating for each glove was determined by comparing the average of three maximum force pulls to the barehand average of three maximum force pulls for each subject with the following equation:

$$\%\ of\ barehand\ control = \frac{PF_g}{CV_b} \times 100$$

where:

PF_g = average pulling force with gloves and,

CV_b = bare-handed control value.

An average grip rating for each of the twenty-four glove pairs was calculated by averaging the percent of barehand control values for each of the five test subjects.

7.1.3 Horizontal Wet Rope Pull: Free Stance

The twenty-four wet-conditioned glove pairs were also tested for grip performance with the wet-conditioned horizontally-oriented rope while gripping the rope, hands slightly more far apart, in a tug-of-war type stance with the body opening up toward the subject’s right.

7.1.4 Vertical Wet Rope Pull

The twenty-four wet-conditioned glove pairs were tested for grip using a vertically positioned wet-conditioned rope attached to a force gauge. A stance apparatus was positioned to ensure subjects stood away from the hanging rope so that their arms, when grasping the rope formed a 90-degree angle. Subjects, grasping with one hand above the other and with knees slightly bent, pulled downward, with arms only, against the rope, without regripping, for 2.5 seconds while force output was continuously recorded.

7.1.5 Vertical Dry Pole Pull

The twenty-four glove pairs were also tested for grip in dry conditions in the same manner as the vertical wet rope test, but instead, a 1.25 in-diameter (31.75 mm) fiberglass pole was vertically mounted, hanging from the force gauge. The stance apparatus and vertically mounted pole are shown in Figure 7.2.

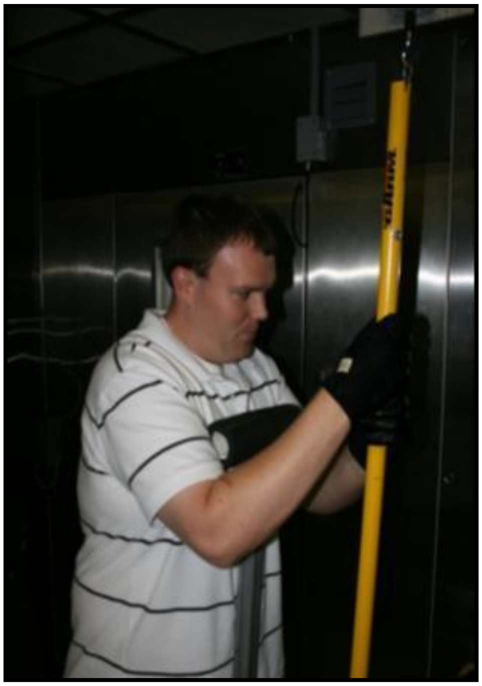

Figure 7.2 Vertical Pole Pull

7.1.6 Vertical Wet Pole Pull

The vertical pole test was repeated for all twenty-four gloves pairs in wet conditions.

7.1.7 Dry Torque Test

An acrylic pole with a 1 5/8 inch-diameter (45.275 mm) was vertically oriented on a calibrated digital torque meter capable of measuring up to 88.5 lb-in (10.00 N-m). The right-hand of each glove pair was tested for grip performance in that each subject, while standing, grasped the pole with his/her right hand so that the arm formed a 90-degree angle [25] and the elbow was close to the hip. The subject twisted the pole with maximum voluntary force in the “open” or counter-clockwise direction for 2.5 seconds [25] while force output was continuously recorded. The apparatus and sample output data are shown in Figure 7.3.

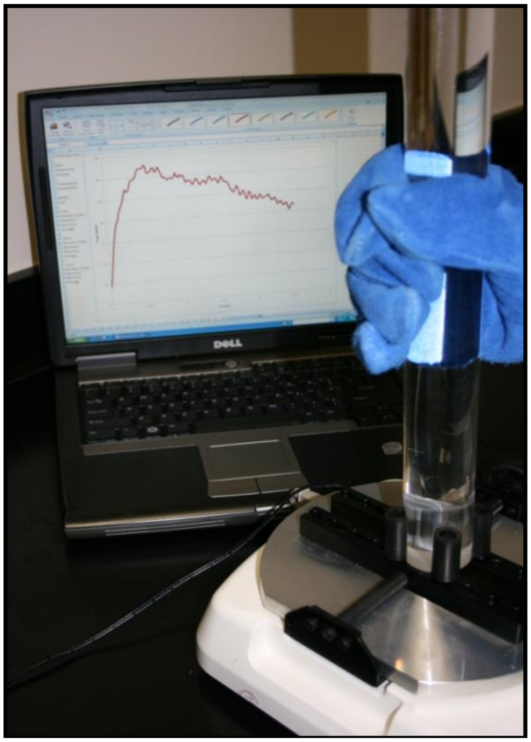

Figure 7.3 Torque Test (Pole Twist)

The preliminary work to develop this method tested PVC pipe with six difference inner diameter sizes: (0.50 in, 0.75 in, 1.00 in, 1.25 in, 1.50 in, 2.00 in) or (12.7 mm, 19.05 mm, 25.40 mm, 31.75 mm, 38.10 mm, 50.80 mm). The twist direction and final pole diameter selection of 45.275 mm agrees with the findings of Kong and Seo, [25; 26; 27].

7.1.8 Wet Torque Test

The twenty-four right hand gloves were also tested for grip in wet conditions in the same manner as the dry torque test, but under wet conditions.

Chapter 8. Grip Study Results and Discussion

Four grip tests were conducted to evaluate the grip performance of structural firefighting gloves. Once reliable test methods were determined, statistical analyses were conducted to determine the relationships between glove materials and construction and the grip performance measured by these test methods.

8.1 Human Subjects

Five human subject evaluators participated in this study. This right hand-dominant group included four males and one female all of college-age. The number of subjects chosen is identical to the experimental procedure by Dodgen [9]. The whole-glove hand form apparatuses used in this study were designed to fit large sized gloves, so subjects were selected on the condition that the right hand fit a large glove. Fit is a very important factor in glove hand function performance, so to achieve the best possible fit and to subsequently control for fit, subjects were selected if no more than two of the twelve hand measurements were outside of the sizing recommendations for large size gloves specified in NFPA 1971 [16].

8.2 Grip Performance Assessed Using the NFPA 1971 Method

NFPA 1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting specifies that "gloves shall be tested for grip as specified in Section 8.9, Grip Test and shall have a percentage of barehand control value of not less than 90," [11]. Figure 8.1 shows that ten of the nineteen NFPA 1971 compliant gloves fail the grip test. Many more barely pass this grip performance test. Figure 8.1 represents the average grip ratings of five subjects. Some of the ratings are so dissimilar that gloves that pass with one subject, all fail when tested by a different subject. The high variability within this test could make it easy to choose a test subject for a desired glove performance outcome: either pass or fail. Therefore, there is a need for improved grip characterization test methods for structural firefighting gloves.

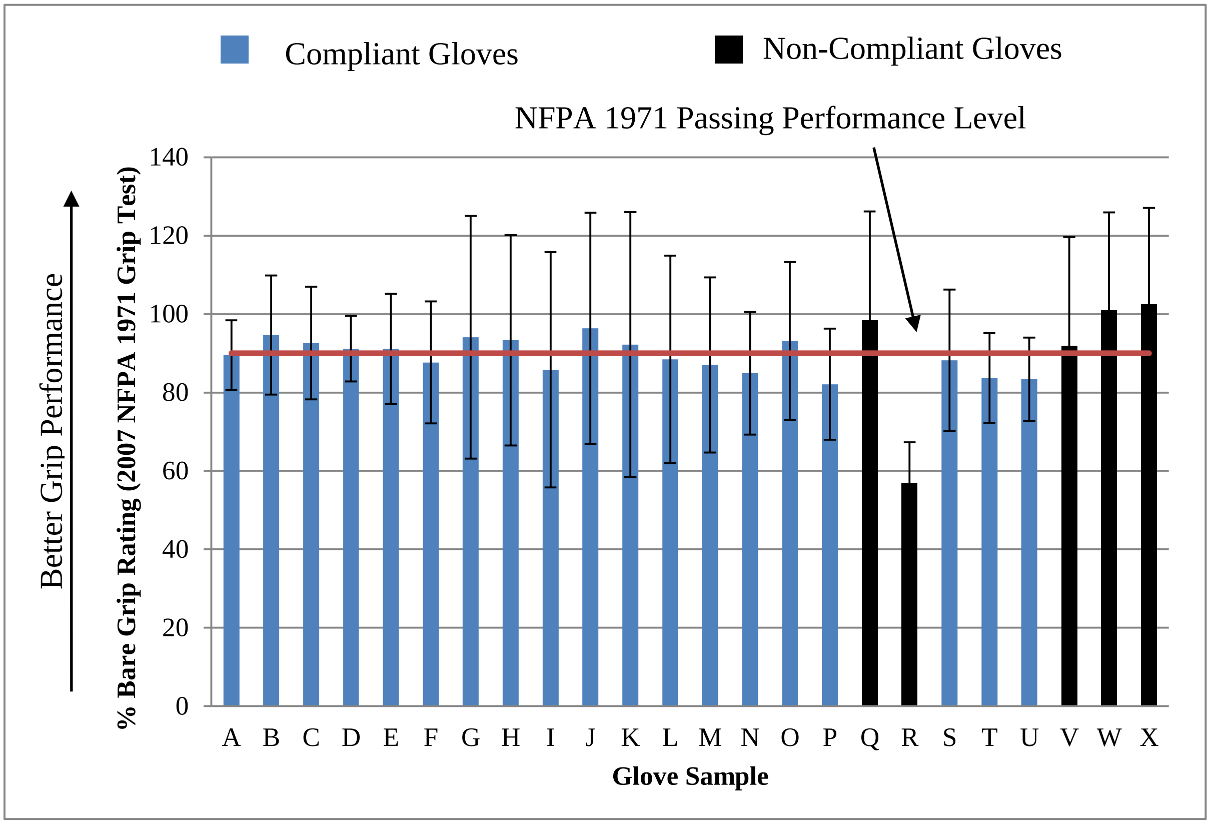

Figure 8.1 Grip Performance in Wet Horizontal Rope Test (Fixed Stance)[18]

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[18] Gloves with grip ratings that fall above the performance limit line are gloves that pass the NFPA 1971 standard test for grip performance

8.3 Comparing Grip Test Methods Based on Variability and Ability to Differentiate Glove Performance

For a test method to be reliable, it should provide low subject-to-subject variability, high discriminating power and an ability to provide a range of grip ratings. When a test method captures a larger range, it is easier to discriminate between gloves based on their grip performance. Discerning if gloves perform differently is important not only for establishing performance requirements, but also for developing better performing gloves. It is important to know how materials and construction affect grip performance. The best way to achieve these goals is with test methods that provide low subject-to-subject variability.

8.3.1 Evaluation of Test Measurement Range

To directly compare the measurement ranges of each of the grip tests, the minimum grip rating was subtracted from the maximum rating in each test to obtain the range. Figure 8.2 compares the measurement ranges of the grip tests.

A test method capable of evaluating a large range of measurements helps a test method discriminate between gloves because the values are spread over a larger range. When considering only the NFPA 1971 compliant gloves, the measurement ranges of each test are comparable.

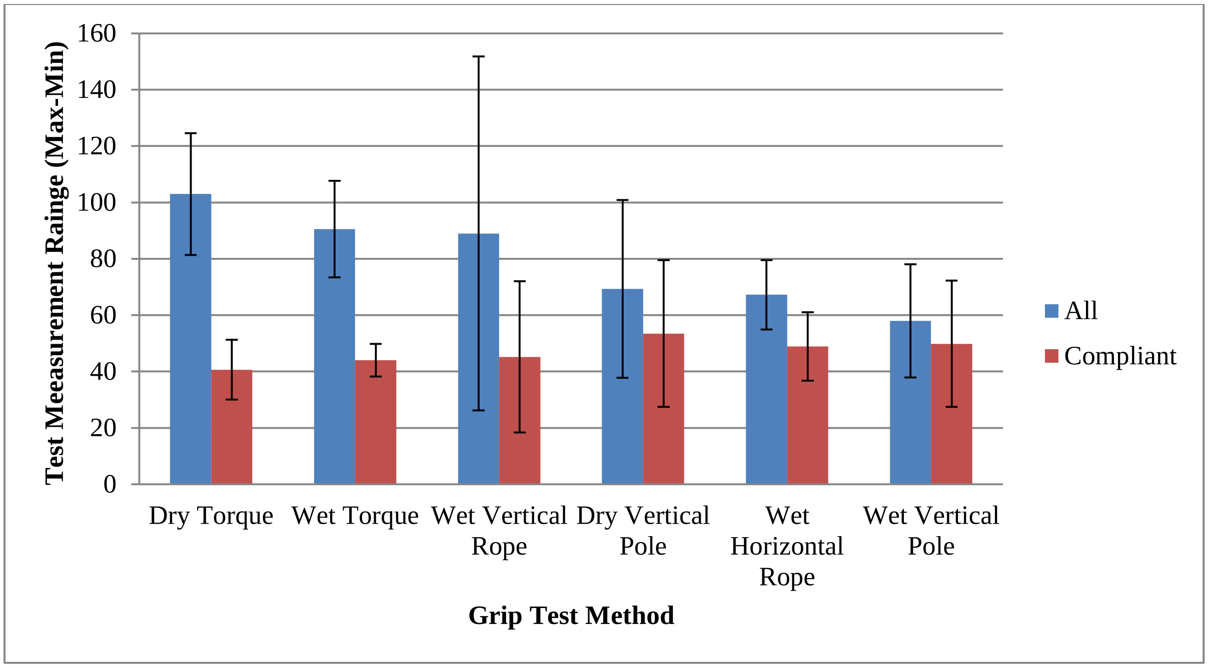

Figure 8.2 Measurement Ranges of Grip Tests[19]

When considering both the NFPA 1971 compliant gloves and the non-compliant gloves, the dry and wet torque tests capture the widest range of grip performances. This finding indicates the ability of the torque tests to recognize gloves with superior grip, a quality that will become increasingly vital as gloves with better grip capabilities are developed.

8.3.2 Evaluating the Discriminating Power of Grip Test Methods

Since the ranges represented in Figure 8.2 are based on average grip ratings from five subjects, it is essential to determine how closely these ratings agree between subjects lest a false confidence about certain test methods arises.

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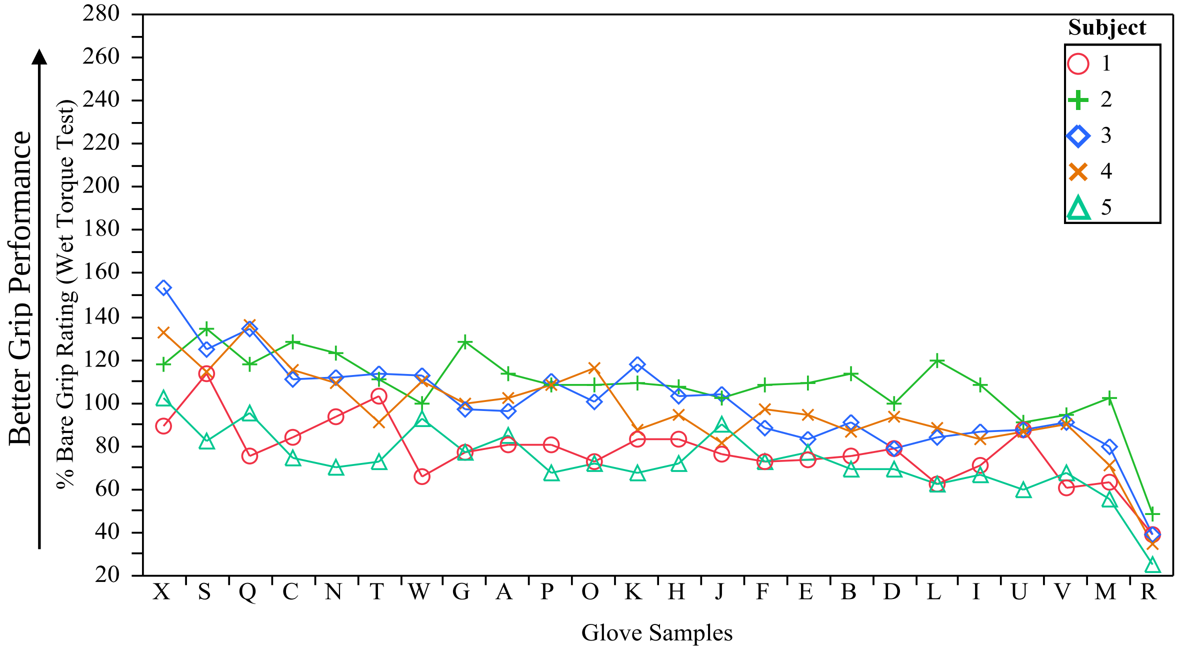
[19] Error bars represent the average standard deviation of the range measurements for each of five subjects.

Figure 8.3 through Figure 8.8 show the subject-to-subject variability for each glove measured by each of the grip tests. A connected letters report accompanies each of the graphical analyses to provide statistical information about how well each test can discriminate between gloves. For all six test methods, subject-to-subject variability is highest for gloves whose grip performance is best, an opposite relationship from that observed in the dexterity study. In most cases, as grip performance increases, agreement between subjects decreases. However, in some cases, like the wet horizontal rope test, there seems to be little relationship between variability and grip performance. Although some of the variability among subjects depends on the specific level of glove performance, the ultimate goal is to determine a grip test method whose overall subject-to-subject variability is minimized.



Level	6 5 4 3 2 1	A	B A	C B A	D C B A	D C B A	D C B A	E D C B A	E D C B	E D C B	E D C B	E D C B	E D C B	E D C B	E D C	E D	E D	E D	E D	E D	E D	E D	E D	E	F
Avg.		119.1	113.8	111.7	102.5	101.6	98.3	96.4	95.9	95.7	95.2	94.2	93.1	92.3	90.9	88.0	87.5	87.4	84.2	83.5	83.2	82.5	80.8	74.5	37.3

Figure 8.3 Subject-to-Subject Variability in Wet Torque Test[20]

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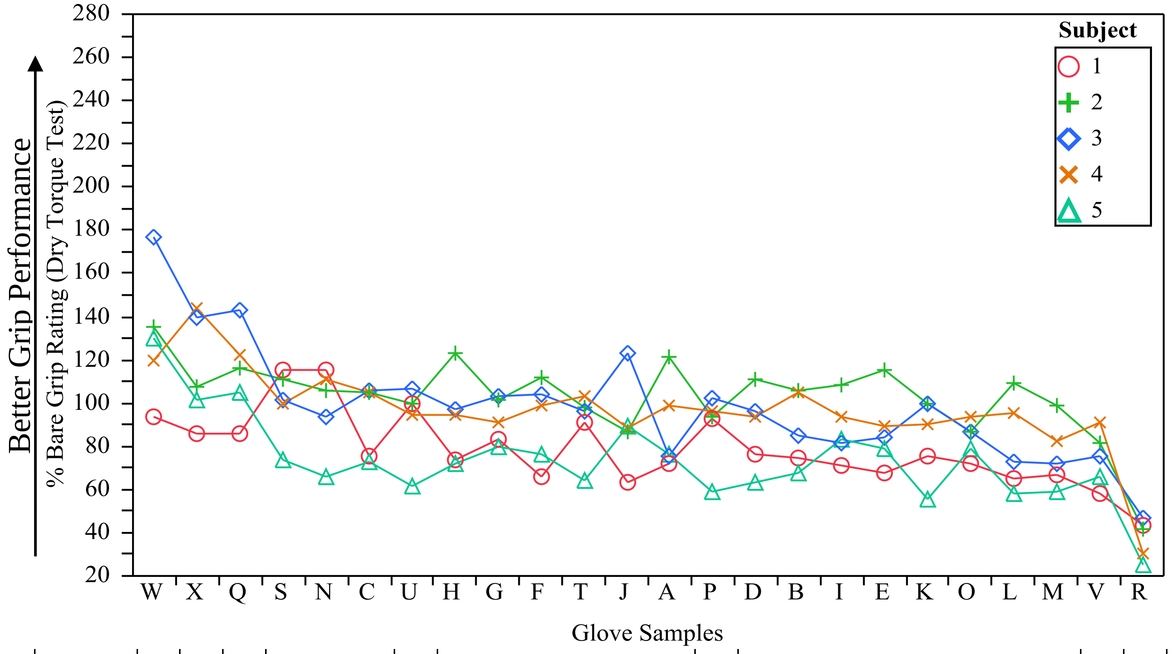
[20] Connecting letters report is provided by collection of student's t-tests performed at the alpha=0.05 significance level. Gloves connected by the same letter do not have significantly different grip performances.



Level	7																								G
	6																								F
	5							E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	
	4				D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D		
	3			C	C	C	C	C	C	C	C	C	C	C	C										
	2		B	B	B	B	B	B	B	B	B	B	B	B											
	1	A	A	A	A	A	A	A																	
Avg.		131.1	115.7	114.4	100.1	98.4	92.9	92.4	92.2	91.8	91.5	90.7	90.1	88.8	88.8	87.9	87.7	87.4	86.9	83.5	83.4	80.3	75.7	74.4	37.4

Figure 8.4 Subject-to-Subject Variability in Dry Torque Test[21]

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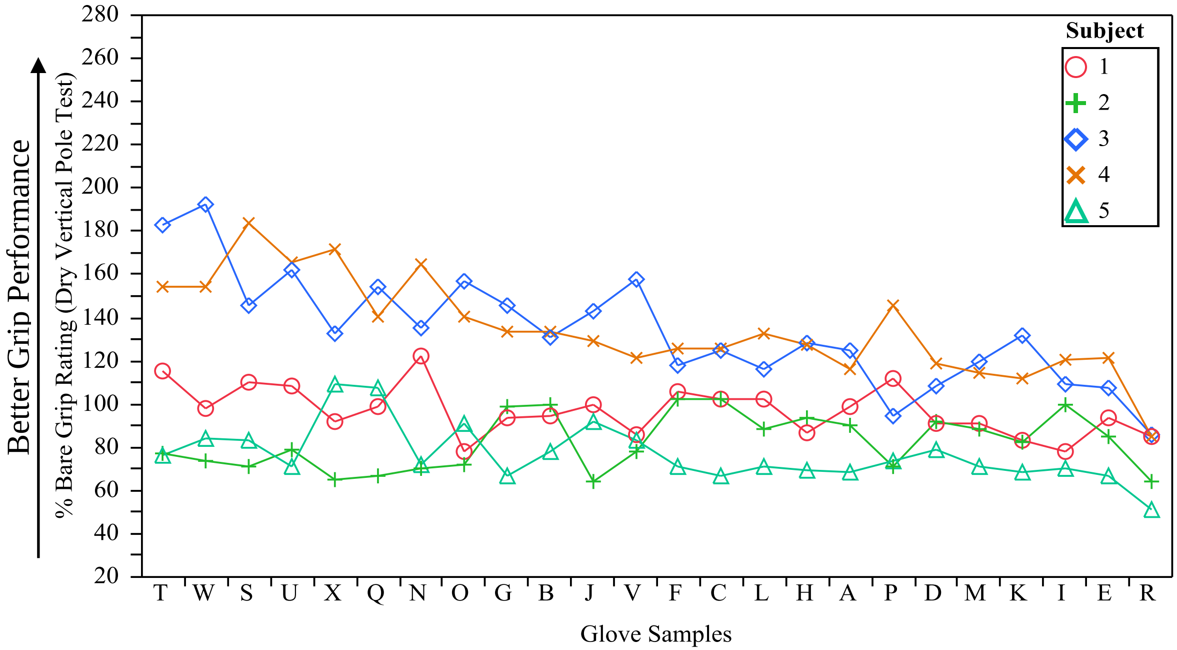
[21] Connecting letters report is provided by collection of student's t-tests performed at the alpha=0.05 significance level. Gloves connected by the same letter do not have significantly different grip performances.



		T	W	S	U	X	Q	N	O	G	B	J	V	F	C	L	H	A	P	D	M	K	I	E	R
Level	2					B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	
Avg.		121.3	120.7	118.7	117.2	114.3	113.6	112.9	107.6	107.5	107.3	105.3	105.2	104.6	104.4	102.3	101.1	99.7	99.4	97.5	96.9	95.8	95.6	94.7	74.1

Figure 8.5 Subject-to-Subject Variability in Dry Vertical Pole Test[22]

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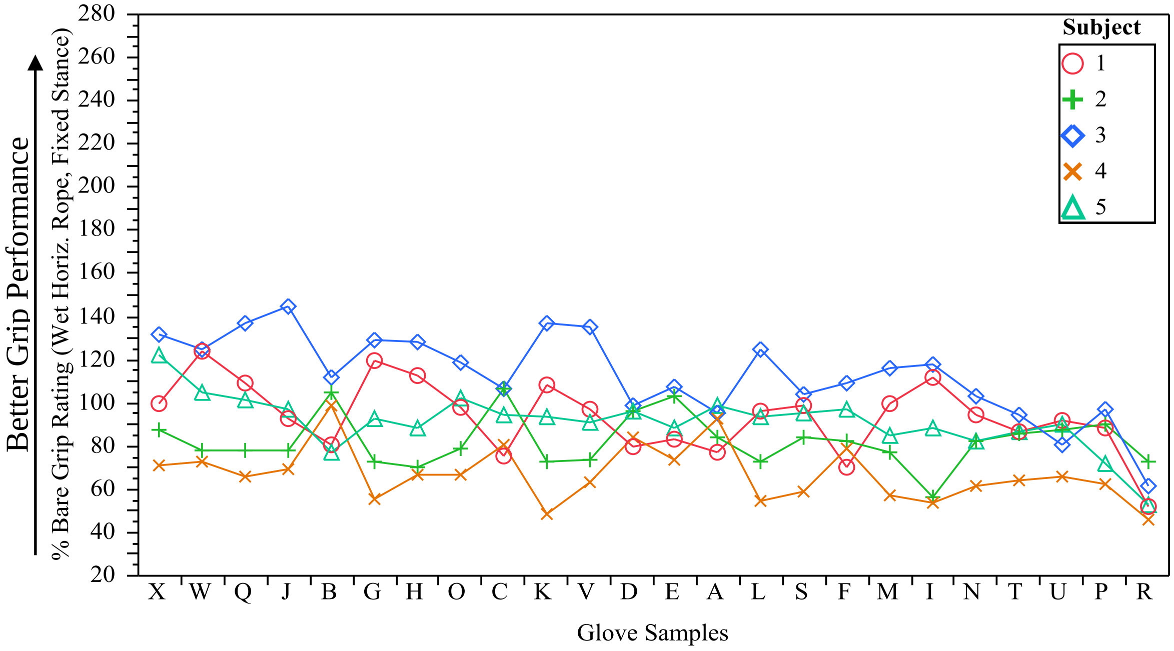
[22] Connecting letters report is provided by collection of student's t-tests performed at the alpha=0.05 significance level. Gloves connected by the same letter do not have significantly different grip performances.



Level	2																					B	B	B	B
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	
Avg.		102.5	101.0	98.4	96.3	94.6	94.1	93.3	93.1	92.6	92.2	91.9	91.2	91.2	89.6	88.5	88.2	87.7	87.0	85.8	84.9	83.7	83.4	82.1	56.9

Figure 8.6 Subject-to-Subject Variability in Wet Horizontal Rope Test, Fixed Stance[23]

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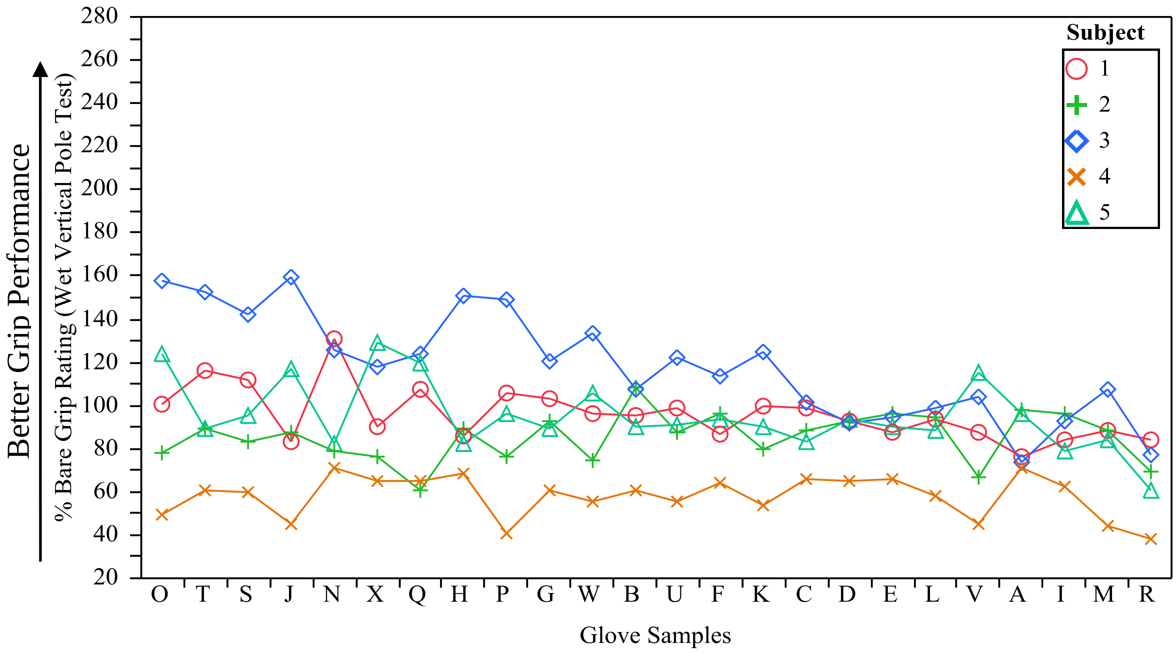
[23] Connecting letters report is provided by collection of student's t-tests performed at the alpha=0.05 significance level. Gloves connected by the same letter do not have significantly different grip performances.



Level	2			B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	
Avg.		102.0	101.6	98.6	98.3	97.9	95.8	95.5	95.4	93.6	93.2	93.2	92.6	91.1	90.6	89.8	87.8	87.4	86.9	86.7	83.7	83.0	82.7	82.5	66.0

Figure 8.7 Subject-to-Subject Variability in Wet Vertical Pole Test[24]

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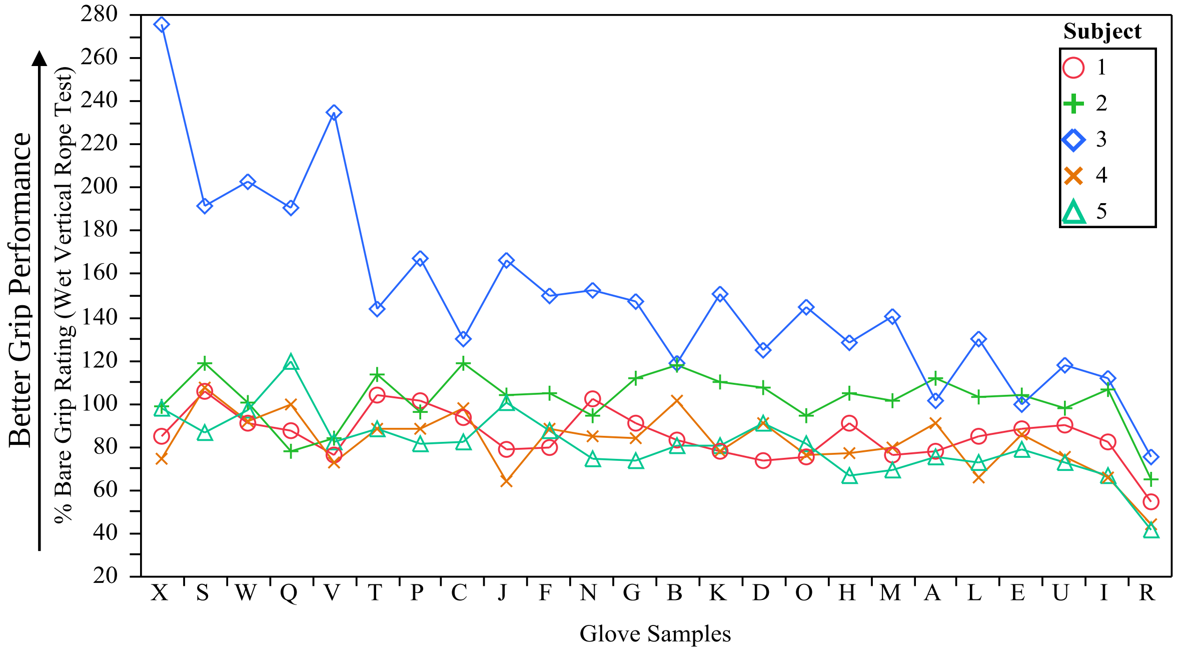
[24] Connecting letters report is provided by collection of student's t-tests performed at the alpha=0.05 significance level. Gloves connected by the same letter do not have significantly different grip performances.



Level	2													B	B	B	B	B	B	B	B	B	B	B	B
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	
Avg.		126.4	121.9	116.6	115.1	110.1	107.6	107.1	104.5	102.9	102.0	101.8	101.6	100.6	99.5	97.8	94.5	93.6	93.4	91.5	91.5	91.4	90.9	86.7	56.4

Figure 8.8 Subject-to-Subject Variability in Wet Vertical Rope Test[25]

The data presented in Figure 8.3 through Figure 8.8 show that the wet and dry torque tests produce lower subject-to-subject variability than any of the other four tests. A collection of student's t-tests was used to identify the grip test method with the least variability and as a result, the most discriminating power. A connecting letters report accompanies the graphical analysis and provides detailed information about which gloves are similar to one another. A higher number of distinguishable grip levels (as indicated by the

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[25] Connecting letters report is provided by collection of student's t-tests performed at the alpha=0.05 significance level. Gloves connected by the same letter do not have significantly different grip performances.

number of letters) is the best indication of low variability within a test method, and therefore more discriminating power.

A summary of the variability analyses and the ability of each test to distinguish gloves by grip performance in shown in Table 8.1.

Table 8.1 Grip Test Method Variability Summary

Grip Tests	Compliant Gloves		Levels of Discrimination	All Gloves		Levels of Discrimination
	Avg. SD	Avg. %CV	t-tests at 95% confidence level	Avg. SD	Avg. %CV	t-tests at 95% confidence level
Dry Torque	17.31	19.49	2	17.79	19.79	7
Wet Torque	17.44	19.05	3	17.73	19.50	6
Wet Horiz. Rope	19.28	21.44	1	20.07	22.19	2
Dry Vert. Pole	24.45	26.21	1	24.90	27.11	2
Wet Vert. Pole	29.27	27.53	1	30.51	28.54	2
Wet Vert. Rope	25.60	25.66	2	31.16	30.14	2

These analyses show that the wet horizontal rope grip test (fixed stance) provides only two distinguishable grip levels. This means that sixteen compliant gloves have indistinguishable grip performance in this test. Furthermore, the second level distinguishes only a non-compliant glove (R) from sixteen compliant gloves and four non-compliant gloves as seen in Figure 8.6. All three vertical pull tests are worse discriminators than the horizontal test but comparable to each other at two levels.

The wet and dry torque tests provide six and seven distinguishable grip levels respectively shown in Figure 8.3 through Figure 8.8. This finding indicates that both test methods have sufficiently low subject-to-subject variability to distinguish non-compliant gloves from compliant gloves, and compliant gloves from each other. T-test analyses indicate that the wet and dry torque tests are the least variable test methods. These methods, therefore, have the greatest ability to measure differences in grip performance.

8.4 Comparing the Wet and Dry Torque Tests

Since the wet and dry torque tests are more reliable than any of the other five grip tests, a bivariate analysis, shown in Figure 8.9, was conducted as ascertain how well these two test methods agree.

Table 8.2 Wet Torque Test/Dry Torque Test Correlation Summary Table

	Correlation between Wet Torque Test and Dry Torque Test	
	Pearson's Correlation Coefficient	Spearman's Rho
Non-Compliant & Compliant	0.8348	0.7774
Compliant Only	0.7421	0.5982

Table 8.2 summarizes the correlation between the wet and dry torque test methods where Pearson’s and Spearman’s correlation coefficients were calculated for the entire group

of gloves and then for only the compliant gloves. In all cases, the correlation coefficients are high, indicating that these two tests provide similar grip measurements.

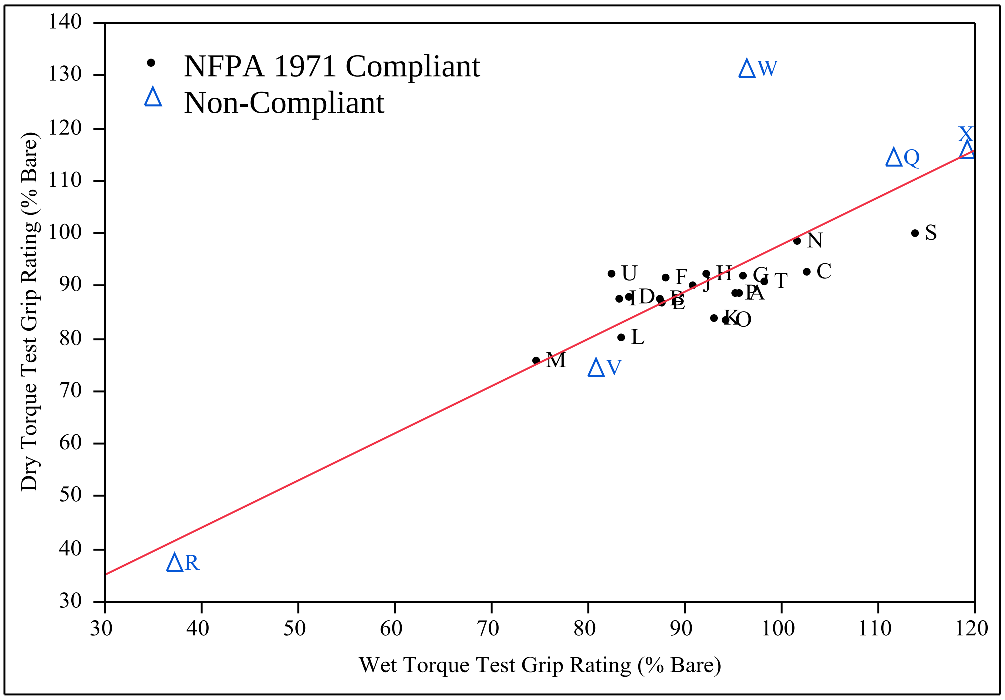

Figure 8.9 Wet and Dry Torque Test Correlation by Grip Performance Rating

There are notable differences, however, in the wet and dry torque test grip performance ratings for some of the gloves. Figure 8.10 catalogs all twenty-four gloves by decreasing wet and accompanying dry grip performances.

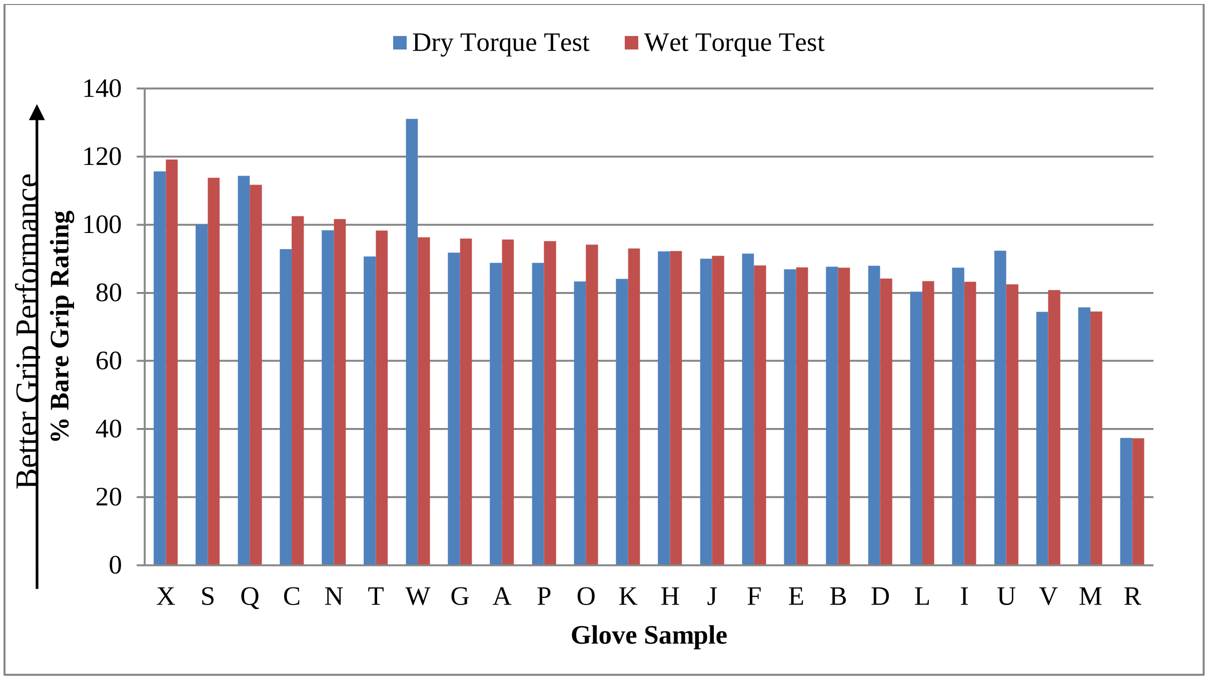

Figure 8.10 Grip Performance of NFPA 1971 Compliant and Non-Compliant Gloves

Most gloves in the study reduce grip performance in relation to the bare hand, but a few show a marked improvement (noted by those ratings that exceed 100%). Most of the twenty-four gloves have dry and wet grip performance ratings that are comparable to one another, but some gloves with synthetic material on the palms (W, U) have drastically decreased wet grip performance. It is evident that the wet torque test has the ability to detect a reduced grip performance in gloves with rubber or silicone coated palm materials. Glove W is a thin knitted glove with a rubberized palm designed for lab work. It has excellent grip in dry conditions, but its grip performance is greatly reduced in wet conditions. Glove U is a 3-D, cow leather-shelled NFPA 1971 compliant structural firefighting glove. It has good grip performance in dry conditions, but the silicone-coated palm reinforcement hinders grip performance in wet conditions. However, some gloves with non-leather materials on the palm perform poorly in both the dry and wet conditions. Glove R is an NFPA 1971 non-compliant hazmat glove with a woven para-aramid shell. This glove performs poorly in the grip test in all conditions.

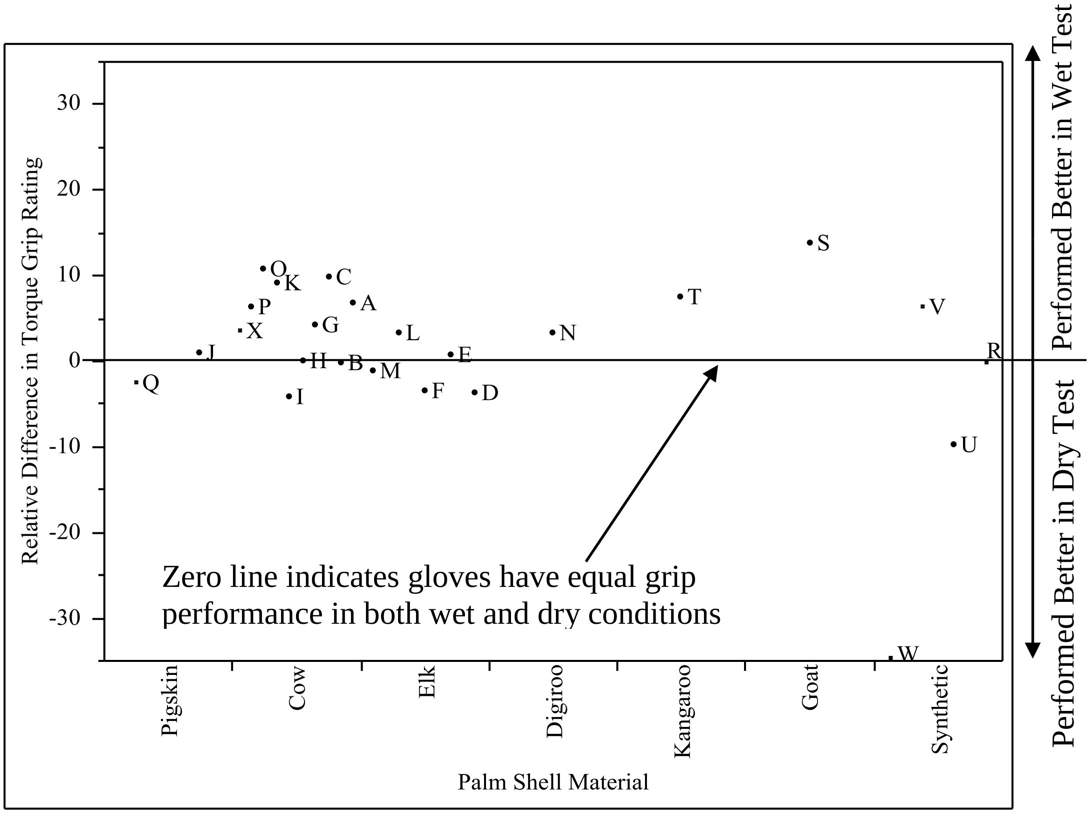

Figure 8.11 Shell Material Effect on Wet and Dry Torque Tests[26]

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[26] This figure represents the difference between the wet torque grip ratings and the dry torque grip ratings. Gloves that fall below the zero line performed better in the dry condition. Gloves that fall above the zero line performed better in the wet condition. Gloves that fall on the zero line performed similarly in both wet and dry conditions.

Figure 8.11 shows that glove shell material alone cannot predict either the wet or dry condition as the worst-case scenario for grip performance. Although many of the gloves perform better in the wet torque test, shell leather type alone is not necessarily a determining factor.

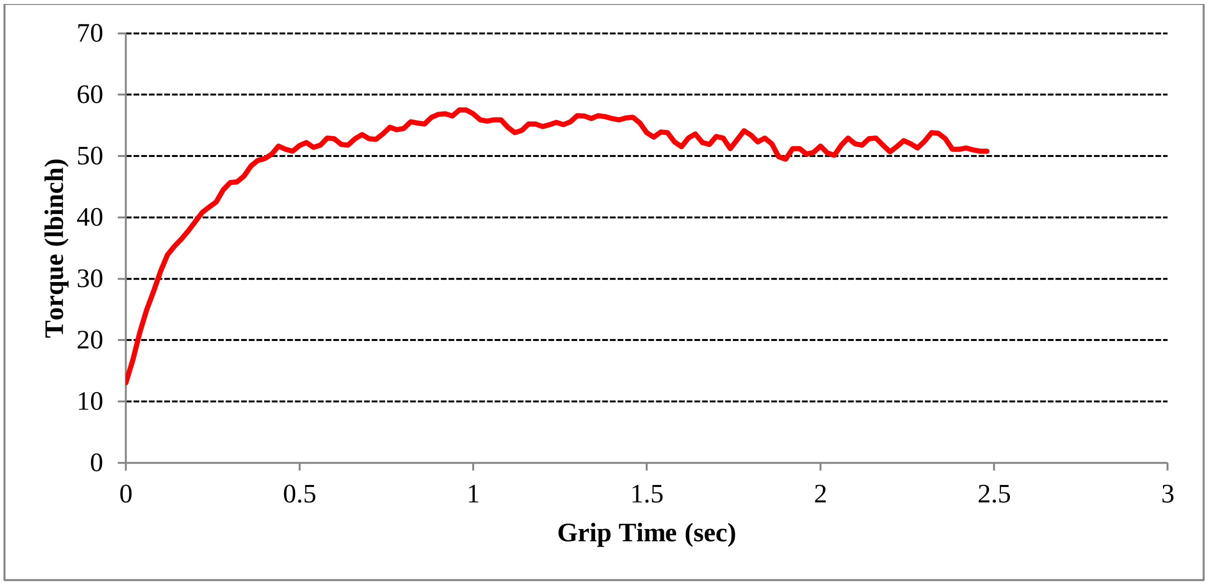

Figure 8.12 Grip Output-Wet Torque Test (Subject 1, Glove I)

Figure 8.12 represents continuous grip output generated by a glove from this study with a leather shell while being tested for grip performance with the wet torque test.

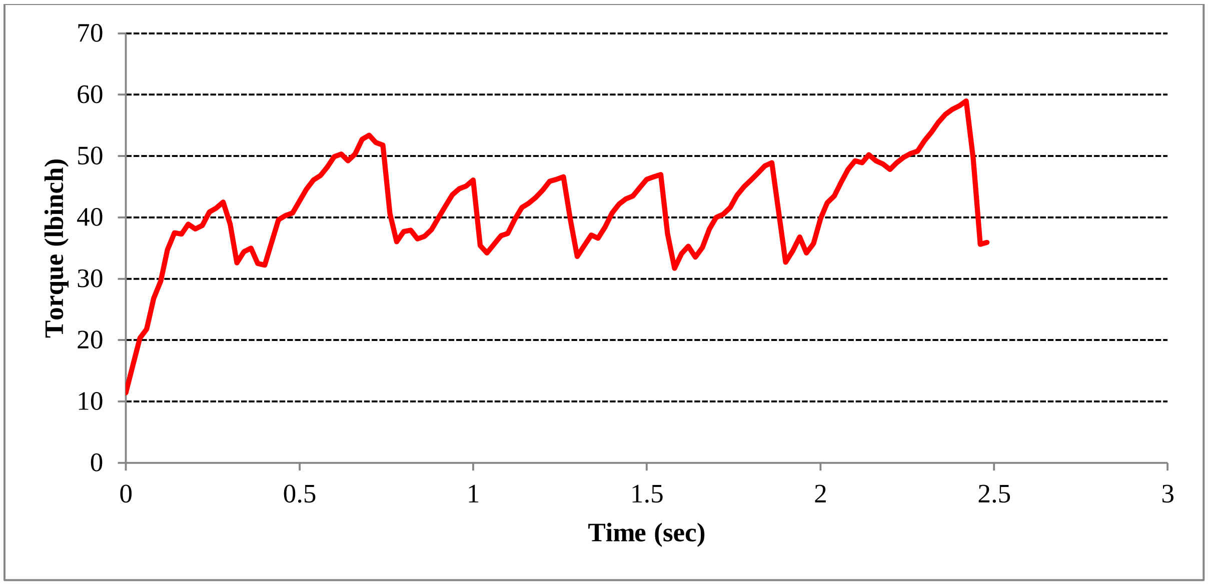

Figure 8.13 Grip Output-Wet Torque Test (Subject 1, Glove W)

Figure 8.13 represents continuous grip output generated by a different glove from this study with a rubberized synthetic shell while being tested for grip performance with the wet torque test. It can be observed that, while these two gloves produce a comparable maximum grip force, the glove in Figure 8.13 experiences a sharp drop-off in grip performance following maximum grip force. The wet torque test also has the unprecedented ability to recognize this phenomenon experienced by firefighters in the field when a wet or slick axe or pike pole slips from their hands, causing a potential hazard.

8.5 Factors Affecting Performance in the Wet Torque Grip Test

The grip performance of structural firefighting gloves depends on the combined effect of constructions and materials. Therefore, it is important to describe grip performance using specific material and constructional attributes of the gloves. This requires determination of the effects of materials and constructions on measured properties used to characterize the glove. Therefore, multiple regression models were developed to investigate these relationships. Table 8.3 summarizes the models related to wet torque test grip performance where an action is given for each predictor per model to increase glove grip performance.

Table 8.3 Wet Torque Test Prediction Models

Model	R^2 Value	Response	Predictors	Action for Better Performance
Partition	60%	Grip Performance	Palm Composite Weight	Decrease
			Palm Shell Material	Elk
7	52%	Grip Performance	Palm Shell Thickness	Decrease
8	81%	Grip Performance	Palm Shell Material	Kangaroo, Digiroo, Goat
			Number of Layers in the Palm	2 or 3

8.5.1 Significant Factors Affecting Grip Performance

Figure 8.14 shows a partition tree graph for the wet torque grip data for the nineteen NFPA 1971 compliant gloves. The model indicates that gloves can be categorized into three levels of grip performance by two factors: palm composite weight and palm shell material.

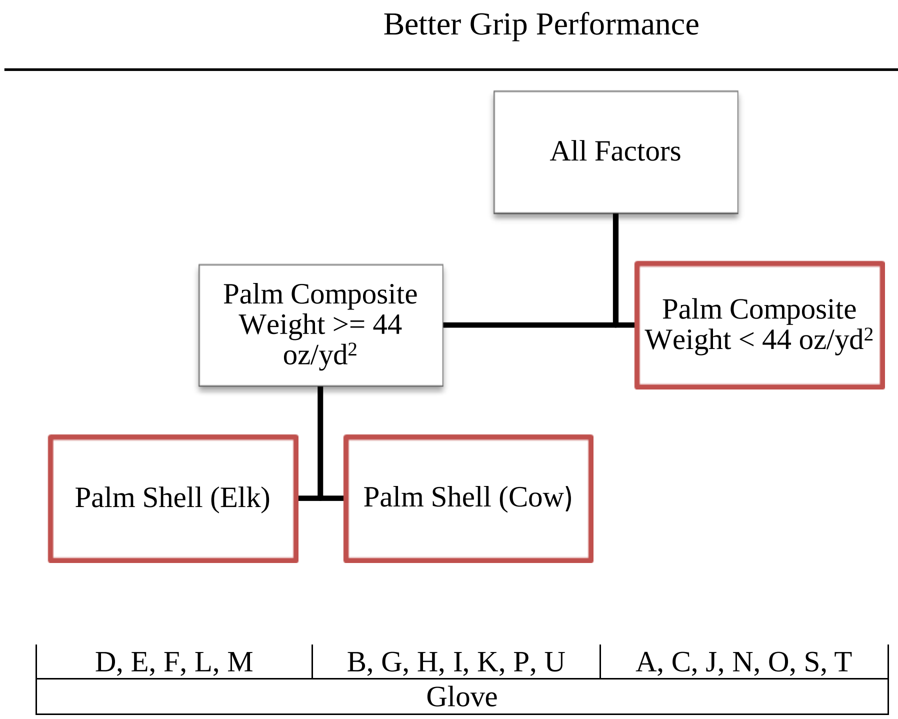

Figure 8.14 Factors Affecting Grip Performance of NFPA 1971 Compliant Gloves in Wet Torque Test (Partition Model)

Gloves whose palm composite weight is greater than 44 oz/yd^2 have poorer grip performance than those with a lower palm composite weight. Gloves whose palm composite weight is greater than 44 oz/yd^2, can be further divided into two grip performance groups by palm shell material. In this case, gloves that incorporate cow leather outer shells perform better than those that use elk leather in the outer shell. Those gloves whose palm composite weight is less than 44 oz/yd^2 will likely have better grip performance regardless of palm shell material. Table 8.4 shows a summary of the criteria, average grip ratings for each group, and the number of gloves within each group for the partition model.

Table 8.4 Wet Torque Grip Rating Averages for Each Partition Group

Grip Performance Category Label	Mean Grip Rating	Number of Gloves
Palm Composite Weight (oz/yd2)>=44.72 & Palm Shell(Elk)	77.4	5
Palm Composite Weight (oz/yd2)>=44.72 & Palm Shell(Cow)	85.0	7
Palm Composite Weight (oz/yd2)<44.72	95.2	7

Since the partition model divides the gloves into categories of grip performance levels by criteria, the model predicts a grip rating for each group of gloves, not individual gloves as shown in Figure 8.15. This figure shows the actual and fitted grip values for this partition model, resulting in an R^2 value of 0.602.

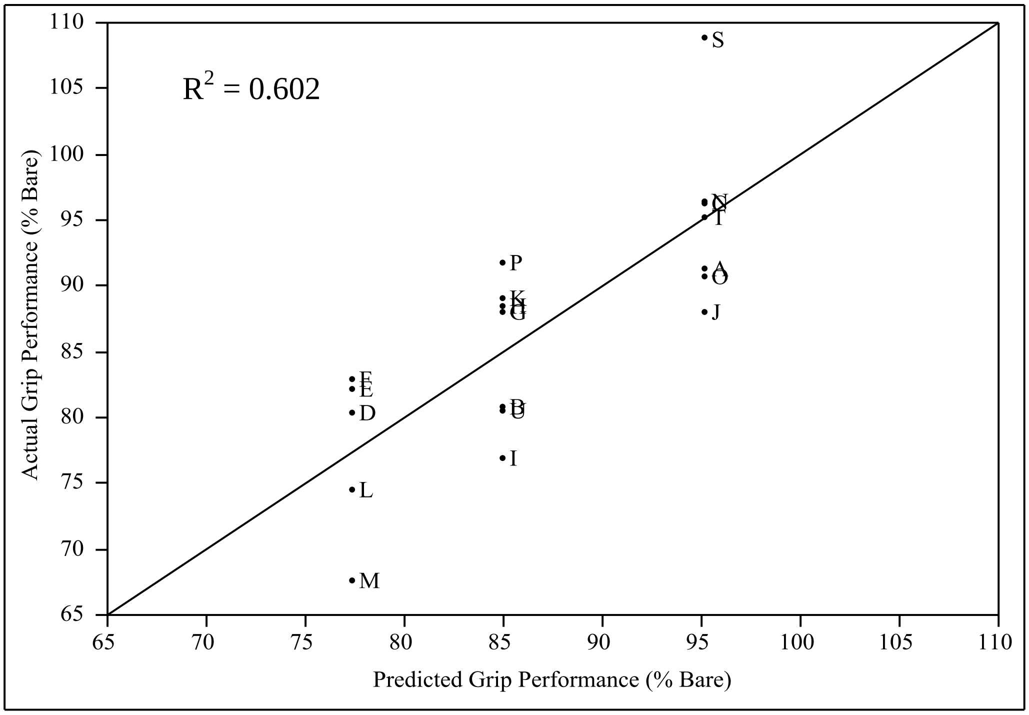

Figure 8.15 Actual Wet Torque Test Grip Ratings by Grip Ratings Predicted by Partition Model

Based on the partition model, when designing a glove with good grip performance, the first goal is to select materials that reduce the weight of the palm layer composite. Since structural gloves usually incorporate two to three layers of materials in the palm, it is important to understand how to assemble multiple layers to provide low palm composite weight.

The combined layers of a structural glove palm must pass a variety of thermal performance standards outlined in the NFPA 1971 Standard [16]. Much of the thermal insulation protection is provided by the thicknesses of the material layers in the palm. Most structural gloves have similar average palm thickness, but the difference lies in the thicknesses of each of the particular layers. When shell thickness is reduced, thermal liner thickness is increased to provide appropriate thermal protection. Likewise, when a thicker shell is used, thinner thermal liners are acceptable because the shell material provides most of the thermal protection. Determining how to distribute the entire composite thickness among layers to achieve the lowest possible composite weight is an important design step for improving grip performance.

Forward stepwise regression analysis was conducted to determine how layer thicknesses (outer shell, moisture barrier and thermal liner) affect palm composite weight. Only palm shell thickness had any significant effect on palm composite weight. The relationship shown in Figure 8.16 indicates that increasing palm shell thickness is the primary contributing factor to increased palm composite weight.

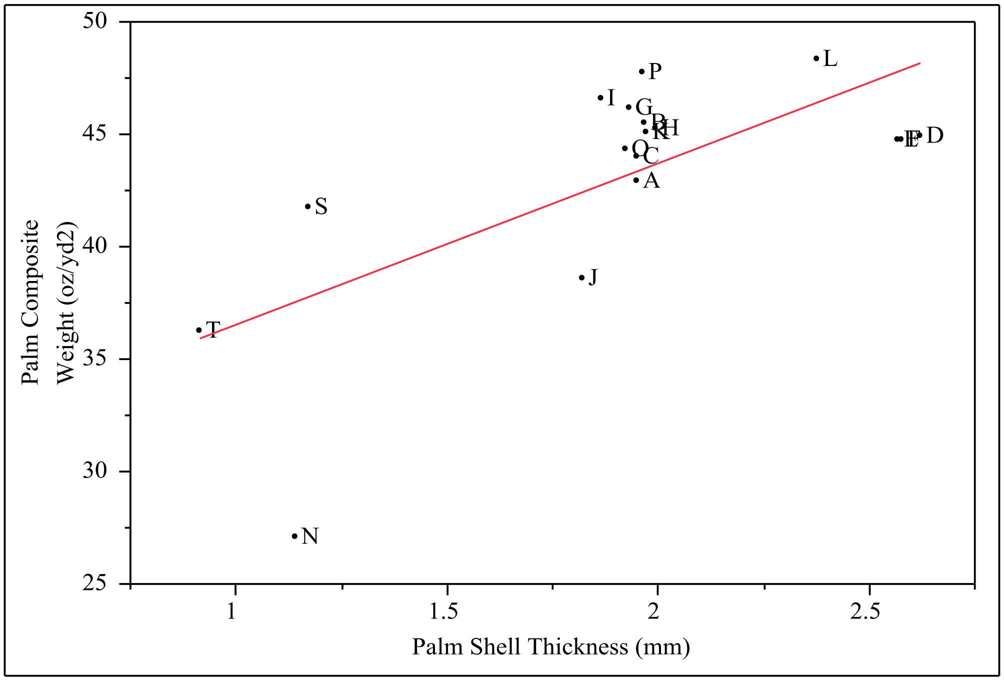

Figure 8.16 Effect of Palm Shell Thickness on Palm Composite Weight

This relationship is so because the density of leather is much higher than that of the thermal liner layers. One millimeter increase in leather thickness raises the palm composite weight much more than a similar increase in thermal liner thickness. To improve the grip performance of structural gloves, therefore, palm outer shell thickness should be minimized to decrease palm composite weight.

Figure 8.17 shows the relationship between wet torque grip performance and the thickness of the palm shell component obtained using forward stepwise selection regression analysis. Even though all factors were included as candidates, only the thickness of the palm shell material had a significant relationship at the alpha = 0.05 level. The prediction equation for grip performance (Model 7) indicates that for every mm increase in palm shell thickness, grip performance is reduced by about 10% of the bare hand value. In this study, palm shell thickness ranged from 3.6 mm to 0.9 mm and wet torque grip rating ranged from 75% to 114% of the bare hand. Therefore, choosing thinner palm shell leathers dramatically increases grip performance.

Model 7

$$\begin{aligned} &Grip\ Performance\ (Wet\ Torque\ Test) \\ &\qquad = 113.01 - 10.63 * Palm\ Shell\ Thickness(mm) \end{aligned}$$

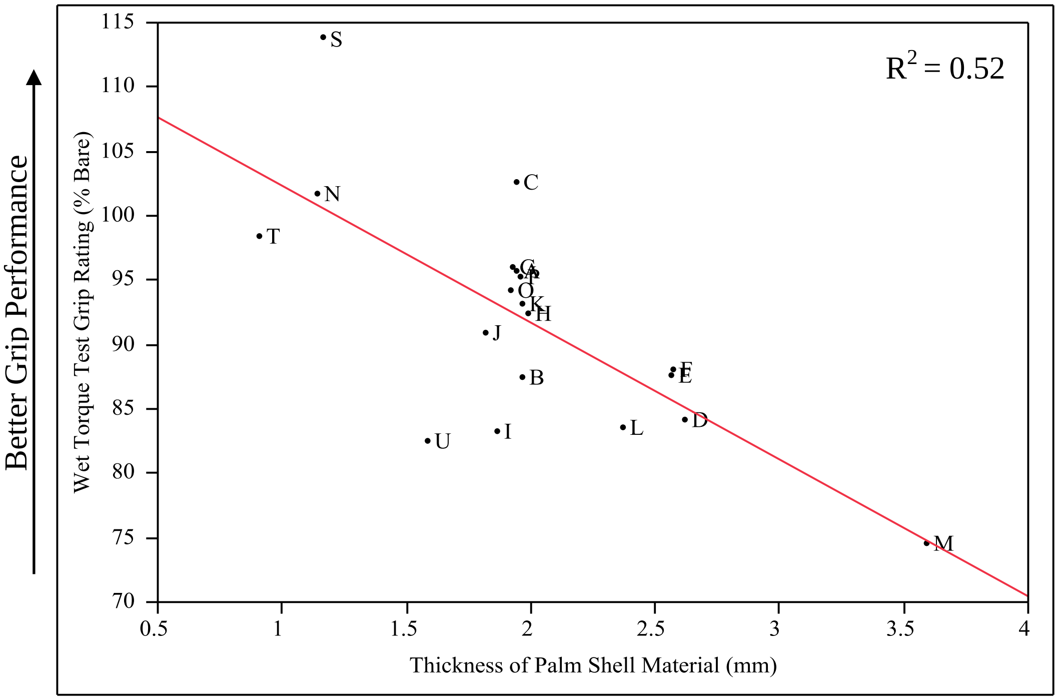

Figure 8.17 Model Prediction of Grip Performance by Palm Shell Thickness

8.5.2 Palm Shell Thickness Relationships

Since palm shell thickness (Model 7) has an influence upon grip performance, it is important from a design point of view to determine if shell thickness is inherent to shell material type. Figure 8.18 shows there are significant differences in palm shell thicknesses by material type. Elk leather is split the thickest, cow and pig are similarly thick, goat and digiroo are slightly thinner and similar to each other, and kangaroo is split the thinnest. This analysis indicates that palm shells made of kangaroo, digitally embossed kangaroo and goat leathers provide better grip.

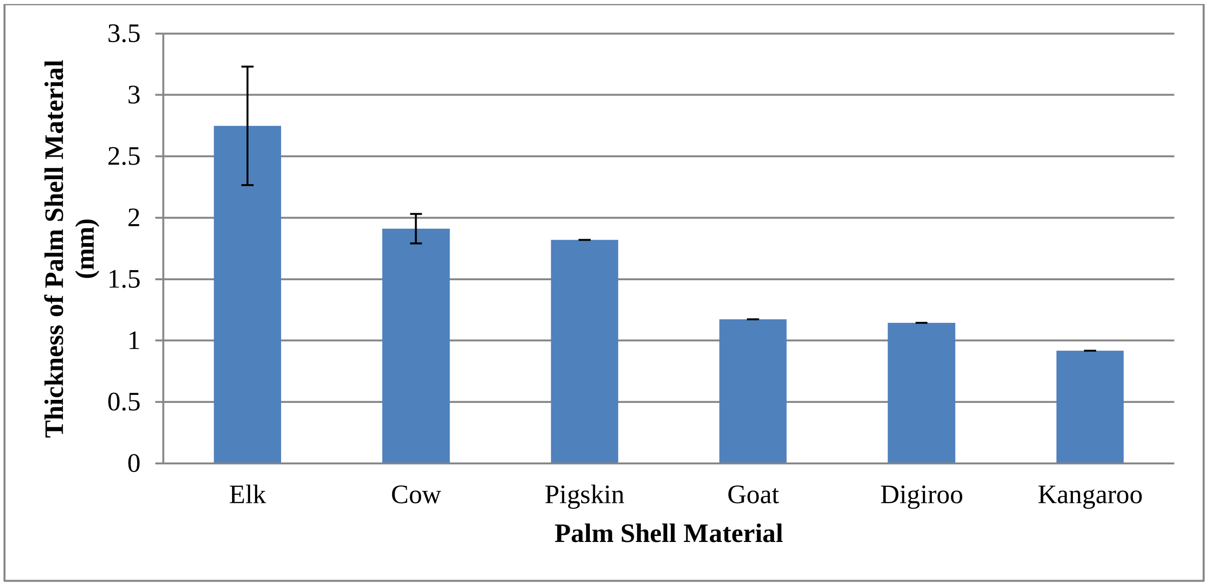

Figure 8.18 Effect of Palm Shell Material on Palm Shell Thickness[27]

While a thinner palm leather material corresponds with better grip performance, it does not guarantee a thinner palm composite. However, this is acceptable because grip

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[27] Error bars show the standard deviation for each group mean.

performance improves with a lower palm composite weight, not a thinner palm composite. Figure 8.19 indicates that most of the gloves, regardless of the type of leather used for the palm shell, have comparable palm composite thicknesses. Only two gloves (S and T) have significantly different palm composite thicknesses from the rest of the gloves. The palm composites of gloves S and T include some of the thinnest outer shell leathers. This indicates that thinner leathers require thickness to be added elsewhere in the palm composite to meet thermal performance requirements. However, grip performance does not depend on palm composite thickness, but on palm leather thickness, a value which if minimized, yields better grip performance.

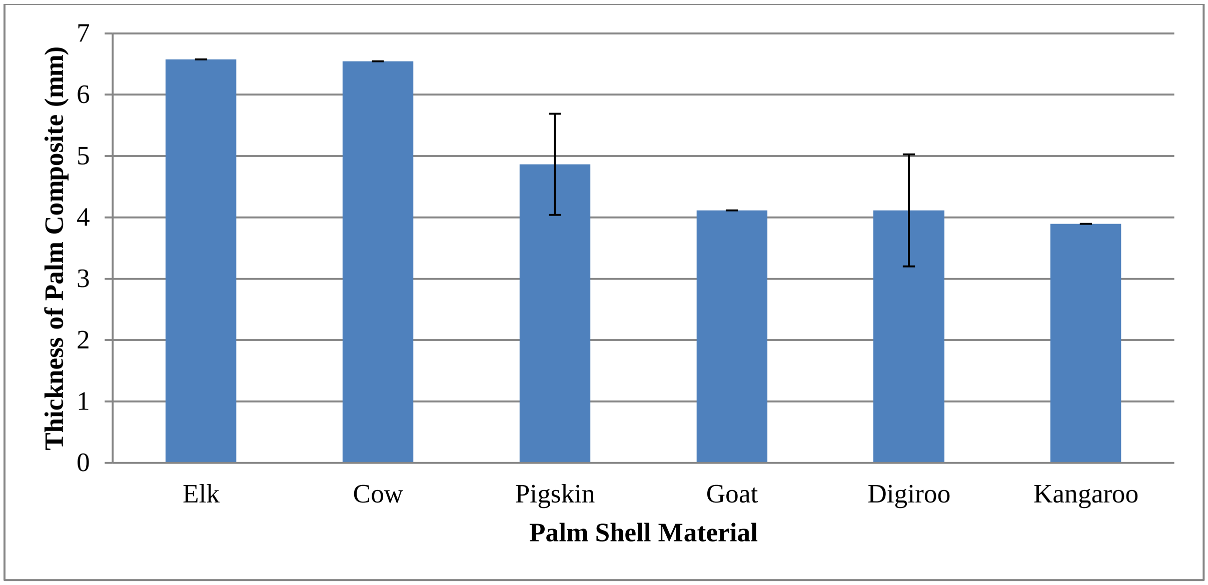

Figure 8.19 Effect of Palm Shell Material on Palm Composite Thickness[28]

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[28] Error bars show the standard deviation for each group mean.

The relationship between palm shell thickness and glove construction was also explored. Table 8.5 shows a significant relationship between palm shell thickness and whole glove construction. On average, the palm shell thickness of 3-D gloves is much less than that of 2-D gloves. It is likely that because of the additional seams[29] in the design, 3-D glove designs are restricted to palm leathers only up to a certain thickness.

Table 8.5 Effect of Glove Construction on Shell Thickness and Wet Torque Grip Performance

Property	Glove Construction		t-test Statistics ($\alpha = 0.05$)
	2D	3D	
Avg. Thickness of Shell Material (mm)	2.22	1.36	Test = 3-D - 2-D
Std. Dev. of Thickness	0.49	0.42	t-Ratio= -3.8065, Prob<t = 0.0024*
Wet Torque Test Grip Rating (% Bare)	89.49	98.28	Test = 3-D - 2-D
Std. Dev. of Grip Rating	6.98	11.31	t-Ratio= 2.64475, Prob>t = 0.0290*

Because palm shell thickness varies significantly between glove construction types and has a significant effect upon grip performance, the relationship between glove construction and grip performance was explored. Table 8.5 also indicates that gloves with a 3-D construction provide significantly better grip performance than do the NFPA 1971 compliant gloves with 2-D constructions.

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[29] 3-D designs include fourchettes (finger side panel composites) between the palm and back sides of the glove. These side panels must be sewn to the palm side and the back side of the glove. This design results in an addition seam along the fingers when compared to 2-D designs.

8.5.3 Material and Construction Factors Affecting Grip Performance

A forward stepwise selection regression analysis was conducted with candidates of only variables that can be identified as levels in discrete categories. By including, for model selection, only categorical glove properties, it is possible to determine how materials and design features specifically affect grip performance.

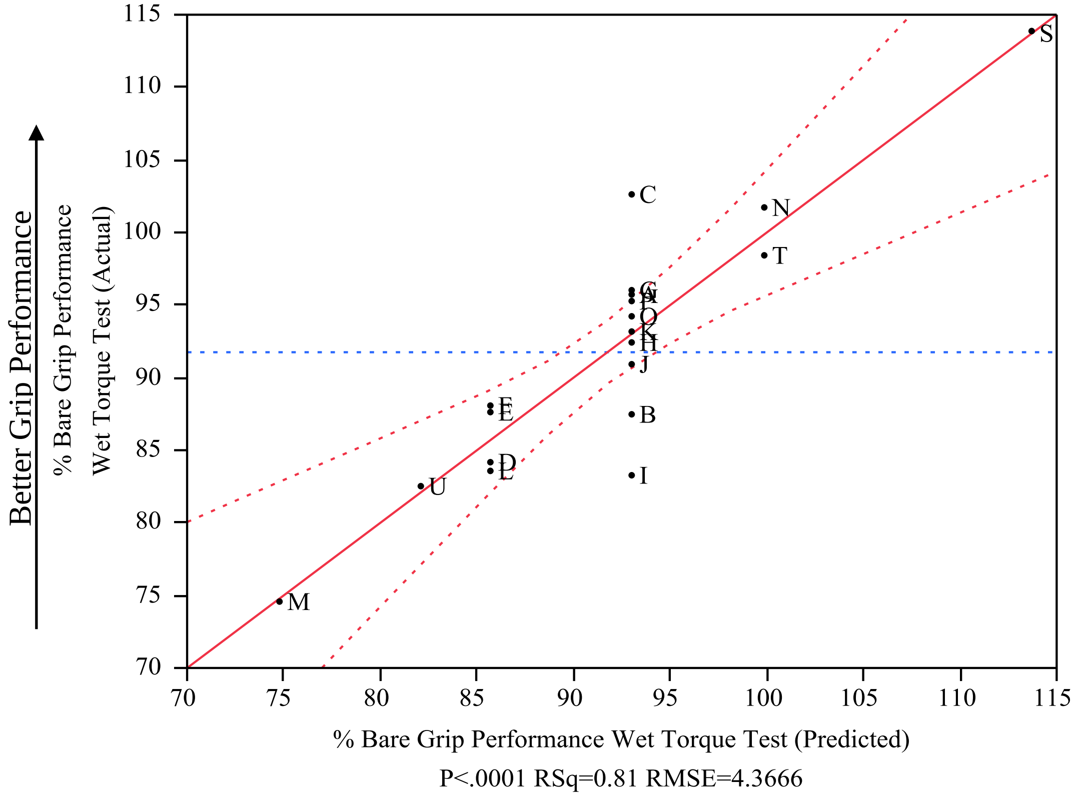

Figure 8.20 Grip Performance Model with Categorical Variables

The fitted model illustrated in Figure 8.20 is composed of three linear combinations based on palm shell material and one based on number of palm composite layers. When including only categorical variables as candidates, palm shell material and number of layers in the palm composite explained 81% of variation in glove grip performances. This analysis suggests that palm design of gloves has a major effect on grip performance.

Model 8

$$
\begin{aligned}
&Grip\ Performance\ (Wet\ Torque\ Test) = 92.69 \\
&-8.75 * Palm\ Shell\{Elk\ \&\ Pigskin\ \&\ Cow - Kangaroo\ \&\ Digiroo\ \&\ Goat\} \\
&-3.67 * Palm\ Shell\{Elk - Pigskin\ \&\ Cow\} \\
&-6.92 * Palm\ Shell\{Kangaroo\&Digiroo - Goat\} \\
&-5.44 * Number\ of\ Palm\ Layers\{4 - 3\ \&\ 2\}
\end{aligned}
$$

Model 8 indicates that, as a palm shell material, kangaroo, digiroo or goat leather provide better grip than elk, pigskin or cow leather. Of the three leather types that deliver the poorest grip (elk, pigskin and cow), gloves with elk palm shells have the poorest grip performance (likely due to the high thickness inherent to elk leathers). Of the three best performing palm leathers (kangaroo, digiroo and goat), gloves with palm shells made of goat leather had the best grip performance.

This model also predicts that gloves with 4 palm layers perform worse than gloves with either 3- or 2-layer palm composites. Model 8 shows that designing a glove with a goat palm shell material incorporated into either a 2- or 3-layer palm composite would provide the best grip performance[30].

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[30] When considering this group of twenty-four test gloves and associated properties.

Chapter 9. Grip Study Conclusions

This research developed a test method that is demonstratively better than the current NFPA 1971:2007 standard method for grip performance. Both the wet and dry torque tests are much less variable than pull-type grip tests regardless of direction of the pulling action. Because they are less variable, torque tests can discriminate between grip performances of structural firefighting gloves. They eliminate the variability introduced by stance, hand placement, pull rate and body position and weight. The wet torque test recognizes a drastic decrease in grip performance (as compared to the dry condition) in gloves, particularly those with a coated or non-leather outer material on the palm.

Statistical models were constructed to explain the effect of glove design and material selection on grip performance. They show that a glove's effect on grip performance is particularly impacted by the design of the palm area of the glove. Gloves with a lower palm composite weight perform significantly better than gloves with a higher palm composite weight. Analyses show that decreasing palm shell thickness will increase grip performance. Outer shell thickness is shown to depend on the type of leather; kangaroo, digitally embossed kangaroo (digiroo) and goat generally are thinner leathers and provide better grip performance.

Gloves with two or three layers in the palm provide better grip performance than palm composites with four layers. Three-dimensional gloves employ the thinnest palm shell leathers contributing to superior grip performance in comparison to 2-D gloves, which tend to use thicker palm leathers. A very important finding is that having a thin leather palm shell does not necessarily lead to a thin palm composite. In fact, most of the uncompressed palm thicknesses of the structural firefighting gloves in this study are comparable. Nevertheless, to increase grip performance, it is most important to decrease palm shell thickness, and not necessarily total palm thickness.

Chapter 10. Designing Gloves for Enhanced Dexterity and Grip Performance

In most aspects of protective equipment design, there are functional tradeoffs, but not so with designing for glove grip and dexterity performance. Constructions and materials that improve grip performance generally improve dexterity performance.

Both glove dexterity and grip are improved by reducing the number of material layers in the palm composite and by reducing palm composite weight. In general, 3-D gloves perform better than 2-D gloves in both grip and dexterity performance. However, 2-layer 2-D gloves perform well in the dexterity lift test. Also, a 3-D whole glove design does not improve grip performance if a thick shell leather is used in the palm area. Three-dimensional gloves show good grip performance because the leather used in the palm is thin, compared to the 2-D gloves. Although the top performing gloves in the dexterity tests are 2-layer 2-D gloves, they had midrange grip performances. However, the 3-layer 3-D glove designs that were among the best performing glove in the dexterity tests also were among the best performing gloves in the grip tests.

Therefore, a 3-D glove construction is a good starting basis for improved combined dexterity and grip performance. Grip performance can be improved with the selection of thinner shell materials in the palm of the glove to reduce palm composite weight. While leather is a necessary material for the palm shell of the glove, analyses show that dexterity performance can be improved by using alternative materials in the back of the glove that decrease glove bulk and glove stiffness. Though 3-D gloves that use thin leathers in the fingertips have good grip performance, the fingertip region is even more important to dexterity performance. Though some improvement to dexterity performance can be made by selecting thin flexible leathers and decreasing the number of layers at the fingertip, much of the improvement lies with the construction possibilities. Moving seams and insert connections so that they do not add undue thickness between either the fingertip or finger pad and the object is the ideal solution.

Both dexterity and grip performance can be improved simultaneously by considering a structural firefighting glove as being made up of many different regions and strategically selecting materials and design constructions for the aspect of hand function that is affected by that region.

REFERENCES

1. **Karter, Michael J. Jr.** *Patterns of Firefighter Fireground Injuries.* Quincy, MA : NFPA, 2009.
2. *Effect of Moisture on the Burn Potential in Fire Fighters' Gloves.* **Veghte, James H.** BeaverCreek : Fire Technology, 1987, Vol. 23.
3. **Lawson, J. Randall.** *Fire Fighter's Protective Clothing and Thermal Environments of Structural Fire Fighting.* Springfield : NISTIR 5804, 1996.
4. **NFPA 1971 Technical Committee Task Group on Gloves.** *Structural Glove Survey.* 2010.
5. *The Development and Evaluation of an Ergonomic Glove.* **Muralidhar, A., Bishu, R.R., Hallbeck, M.S.** s.l. : Applied Ergonomics, 1999, Vol. 30.
6. *The Effects of Various Thicknesses of Chemical Protective Gloves on Manual Dexterity.* **Bensel, Carolyn K.** 6, s.l. : Ergonomics, 1993, Vol. 36.
7. **Crawford, J.** *Crawford Small Parts Dexterity Test.* 1985.
8. *Manual Dexterity Evaluation of Gloves Used in Handling Hazardous Materials.* **Plummer, R., Stobbe, T., Ronk, R., Myers, W., Hyunwook, K., Jaraiedi, M.** s.l. : Proceedings of the Human Factors Society-29th Annual Meeting, 1985. Vol. 1985.
9. **Dodgen, C.R., Gohlke, D.J., Stull, J.O., Williams, M.** Investigation of a New Hand Function Test Aimed at Discriminating Multi-layer Glove Dexterity. [book auth.] C.N., Henry, N.W. Nelson. *Performance of Protective Clothing: Issues and Priorities for the 21st Century: Seventh Volume.* West Conshohocken : American Society for Testing and Materials, 2000.
10. *Glove Characteristics Influencing Control Manipulability.* **Bradley, J.V.** 1, s.l. : Human Factors, 1969, Vol. 11.
11. *NFPA 1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting.* 2007.
12. *NFPA 1971 Report on Proposals.* MA : NFPA, 1991.

13. **Bennett, George K.** Bennett Hand Tool Dexterity Test (H-TDT). *TalentLens from Pearson Web site.* [Online] [Cited: January 3, 2011.] http://www.talentlens.co.uk/select/bennett-hand-tool-dexterity-test.aspx.

14. *NFPA 1971 Report on Proposals.* MA : NFPA, 1997.

15. *Protective gloves - General requirements and test methods.* 2010. EN 420.

16. *NFPA 1971 Standard on Protective Ensembles for Structural and Proximity Fire Fighting.* 2007.

17. **McKenna, Mike.** *Chair of NFPA 1971 Task Group on Gloves.*

18. Standard Test Method for Stiffness of Fabric by the Circular Bend Procedure. ASTM D 4032.

19. *Kawabata Evaluation System Operation Manuals.* s.l. : Kato Tech Co, Ltd., 1986.

20. *The Mechanical Properties of Leather.* **Ward, A.G.** 1, s.l. : Rheologia acta, 1974, Vol. 13.

21. *Stratigraphic Analysis of Kangaroo Leathers.* **Stephens, L.J.** Parkville : Jalca, 1987, Vol. 82.

22. *JMP Statistics and Graphics Guide.* s.l. : SAS Publishing, 2010.

23. *Grip-Load Force Coupling: A General Control Strategy for Transporting Objects.* **Flanagan, J. Randall, Tresilian, James R.** 5, s.l. : Journal of Experimental Psychology, 1994, Vol. 20.

24. Broken Thumb. *Arthritis-Symptom.com.* [Online] Consumer Health Information Network, October 2003. http://arthritis-symptom.com/fracture/broken-thumb.htm.

25. *Evaluation of Handle Diameters and Orienations in a Maximum Torque Task.* **Kong, Y.-K., Lowe, B. D.** s.l. : International Journal of Industrial Ergonomics, 2005, Vol. 35.

26. *Investigation of Grip Force, Normal Force, Contact Area, Hand Size, and Handle Size for Cylindrical Handles.* **Seo, Na Jin, Armstrong, Thomas J.** s.l. : Human Factors, 2008, Vol. 50.

27. *The effect of torque direction and cylindrical handle diameter on the coupling between the hand and a cylindrial handle.* **Seo, Na Jin, Armstrong, Thomas J., Ashton-Miller, James A., Chaffin, Don. B.** s.l. : Journal of Biomechanics, 2007, Vol. 40.

28. *A Quantitative Evaluation of Gloves Used with Non-Powered Hand Tools in Routine Maintenance Tasks.* **Mital, A., Kuo, T., Faard, H.F.** s.l. : Ergonomics, 1994, Vol. 37.

29. *Force Capability Differences Due to Gloves.* **Riley, M.W., Cochran, D.J., Schanbacher, C.A.** 2, s.l. : Ergonomics, 1985, Vol. 28.

30. *Glove Size and Material Effects on Task Performance.* **Chen, Y., Cochran, J., Bishu, R.R., Riley, M.W.** s.l. : Proceedings of the Human Factors Society 33rd Annual Meeting, 1989. Vol. 1989.

31. *Effects of gloves on the total girp strength applied to cylindrical handles.* **Wimer, B., McDowell, Thomas W., Xu, X.S., Welcome, Daniel E., Warren, C.** s.l. : International Journal of Industrial Ergonomics, 2010, Vol. 40.

32. *Effects of Surface Friction of Skilled Performance with Bare and Gloved Hands.* **Groth, H. Lyman, J.** 4, s.l. : Journal of Applied Psychology, 1958, Vol. 42.

33. *An Analysis of Grasp Force Degradation with Commercially Available Gloves.* **Cochran, D.J., Albin, T.J., Bishu, R.R., Riley, M.W.** Santa Monica, CA : s.n., 1986. Proceedings of the Human Factors Society 30th Meeting.

34. *Effects of Glove, Orientation, Pressure, Load, and Handle on Submaximal Grasp Force.* **Buhman, D.C., Cherry, J.A., Bronkema-Orr, L., Bishu, R.** s.l. : International Journal of Industrial Ergonomics, 2000, Vol. 25.

35. **Group, NFPA 1971 Glove Task.** *Grip and Hand Function Proposals.* s.l. : NFPA 1971, June, 2010.

36. *Ergonomic Aspects of Aircraft Keyboard Design: The Effects of Gloves and Sensory Feedback on Keying Performance.* **Taylor, R.M., Berman, J.V.F.** 11, s.l. : Ergonomics, 1982, Vol. 25.

37. *Glove Characteristics Influencing Control Manipulability.* **Bradley, J.V.** s.l. : Human Factors, 1969, Vol. 11.

38. *Maximum Voluntary Hand Grip Torque for Circular Electrical Connectors.* **Adams, S.K., Peterson, P.J.** s.l. : Human Factors, 1988, Vol. 30.

39. **Dodge, Y.** *The Oxford Dictionary of Statistical Terms.* s.l. : OUP, 2003.

APPENDICES

Appendix A - Measurement Procedures

A.1 Hand Measurement Procedure

Measurements were taken of the right hand according to the method prescribed in Section 6.7.5 of NFPA 1791, where each of the 12 measurements was measured to the nearest 1/8 inch. Digit Circumference was measured at the proximal interphalangeal point (first knuckle). Digit length was measured from the tip of the finger to the base of the finger crease on the palm side. Hand Circumference was measured across the metacarpal knuckles as shown in Figure A.10.1. Hand length was measured as the straight line distance between the two horizontal lines identified in Figure A.10.1 as the right hand was placed in a flat position with the thumb fully extended.

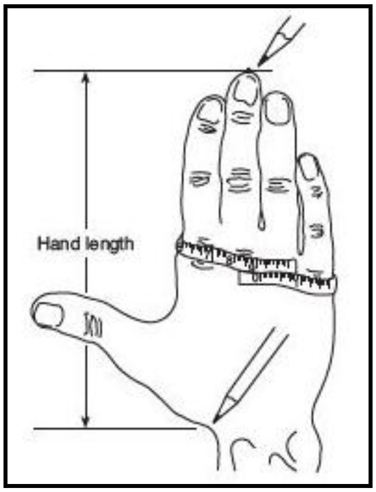


Figure A.10.1 NFPA 1971 Hand Measurement Procedure

Table 10.1 Hand Sizing Data for Human Test Subjects

Subject	1		2		3		4		5	
	Inches	Fit	Inches	Fit	Inches	Fit	Inches	Fit	Inches	Fit
Digit 1 Circumference	2.75	Pass	2.75	Pass	2.625	Pass	2.875	Pass	2.75	Pass
Digit 2 Circumference	2.625	Pass	2.5	Out	2.625	Pass	2.75	Pass	2.75	Pass
Digit 3 Circumference	2.625	Pass	2.625	Pass	2.75	Pass	2.75	Pass	2.75	Pass
Digit 4 Circumference	2.625	Pass	2.5	Pass	2.625	Pass	2.625	Pass	2.5	Pass
Digit 5 Circumference	2.125	Pass	2.125	Pass	2.5	Pass	2.25	Pass	2.125	Pass
Digit 1 Length	2.625	Out	2.75	Out	2.125	Pass	2.5	Pass	2.75	Out
Digit 2 Length	3.25	Out	3.125	Pass	3	Pass	3.25	Out	3	Pass
Digit 3 Length	3.5	Pass	3.5	Pass	3.375	Pass	3.5	Pass	3.5	Pass
Digit 4 Length	3.25	Pass	3.125	Pass	3.125	Pass	3.125	Pass	3	Pass
Digit 5 Length	2.5	Pass	2.625	Pass	2.375	Pass	2.625	Pass	2.5	Pass
Hand Circumference	8.5	Pass	8	Pass	9.25	Out	9.125	Out	8.75	Pass
Hand Length	7.875	Pass	7.875	Pass	7.625	Pass	7.875	Pass	7.75	Pass

A.2 Dexterity Test Method Procedures

A.2.1 Modified Pegboard Test: Knurled Pins

The following describes the apparatus used to conduct this test method:

Pegboard:

The pegboard shall measure 200 ± 13 mm by 200 ± 13 mm with 25 holes each having a diameter of 10.0 ± 0.25 mm and a depth of 13.0 ± 0.5 mm. The holes shall be in a 5 by 5 patterns and each hole shall have a separation of 25 ± 2 mm from adjacent holes

Pins:

The 25 stainless steel pins shall have a diameter of 9.5 ± 0.26 mm and length of 38.0 ± 0.25 mm with a medium knurled 30 degree (25 teeth per in.) surface.

Pegboard Test surface:

The test surface shall be at least 600 by 900 mm with a flat, level, smooth surface having a hardness of 50 ± 5 Shore A.

A.2.2 Lift Test

The method was conducted with the following apparatus, specifications and setup: At the beginning of each repetition, the top of the cylinder was flush with the top of the plane and the gauge was zeroed. The test administrator turned the dial on the incremental lift system, raising the cylinder in 5 mm increments as noted on the digital gauge until the subject could successfully grasp the cylinder with his/her four fingers and thumb of the bare right hand and lift it completely out of the opening. The height in mm was recorded as the first minimum height. For the remaining 4 repetitions, the test administrator would raise the cylinder in smaller increments with the goal of achieving the smallest height on a continuous scale. The smallest height of the 5 repetitions, in mm, was recorded as the barehanded baseline lift height. The procedure was repeated by all 5 subjects for all 24 glove pair specimens.

A.2.3 Tool Test

The following describes the apparatus and set-up for this test method:

Test board:

The test board consisted of two wooden boards, 1 inch in thickness. The first board, cut to 12 inches in height, was attached vertically, with brackets, to the middle of the second board. Four 9/16 inch diameter holes were drilled 2 inches apart in the vertical board; three in a row and then one directly under the center hole of the top row.

Bolt/Washer Assembly:

Four 3/8 in. head x 2.5 in. long coarse thread bolts were pre-assembled with ½ in., 1 in. diameter washers (1/2 in. bolts).

Nuts:

Four nuts were kept separate from the 3/8 in. head x 2.5 in. long coarse thread bolts (1/2 in. bolts).

Fender Washers:

Four ½ in., 1 3/8 in. diameter fender washers were kept separate from the other parts of the assembly.

Tools:

The test subject used two tools during this test: a 3/8 in box-end wrench and a 3/8 in. drive torque wrench with a 3/8 in. deep-well 3/8 in. socket attachment.

Set-up:

The test board was positioned in a comfortable position in front of each test subject. Since each test subject in this series of experiments was right-handed, it was most comfortable to layout the test in the following way:

- The 4 bolt/washer assemblies were laid out on the left side of the test board
- The 4 nuts were laid out on the right side of the test board
- The torque wrench was set to the right side of the test board
- The box wrench was set the left side of the test board
- The 4 fender washers were in the possession of the test facilitator seated across from the test subject

Additional Procedure Specifications:

During the test, when bolt/washer assemblies, nuts or wrenches were dropped onto the test surface, the test subject picked them up, but if they were dropped onto the floor, the trial was stopped and repeated. If fender washers were dropped onto the test surface, the test facilitator picked them up and handed them back to the test subject.

Appendix B – Additional Model Statistics

B.1 Designing for Dexterity, As Measured by the Incremented Lift Test

Model 1

$$\begin{aligned} &Dexterity\ Performance \\ &\qquad = 160.65 + 0.083 * Bulk(cm3) \\ &\qquad - 7.36\ [TL\ to\ MB\ Connection\{Adhesive\ \&\ None\ \&\ Tabs\ sewn\ at\ side \\ &\qquad - Sewn\ to\ MB\ \&\ Double\ sided\ tape\}] \end{aligned}$$

Table B.1 Summary of Fit: Model 1

RSquare	0.840804
RSquare Adj	0.818062
Root Mean Square Error	5.8302
Mean of Response	199.5767
Observations (or Sum Wgts)	17

Table B.2 Analysis of Variance: Model 1

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	2513.3858	1256.69	36.9711
Error	14	475.8773	33.99	**Prob > F**
C. Total	16	2989.2631		<.0001*

Table B.3 Parameter Estimates: Model 1

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	160.64946	10.1715	15.79	<.0001*
Bulk (cm3)	0.0827409	0.020396	4.06	0.0012*
TL to MB Connection{Adhesive&None&Tabs sewn at side-Sewn to MB&Double sided tape}	-7.3597	1.679855	-4.38	0.0006*

Table B.4 Effect Tests: Model 1

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Bulk (cm3)	1	1	559.39344	16.4570	0.0012*
TL to MB Connection{Adhesive&None&Tabs sewn at side-Sewn to MB&Double sided tape}	1	1	652.44454	19.1945	0.0006*

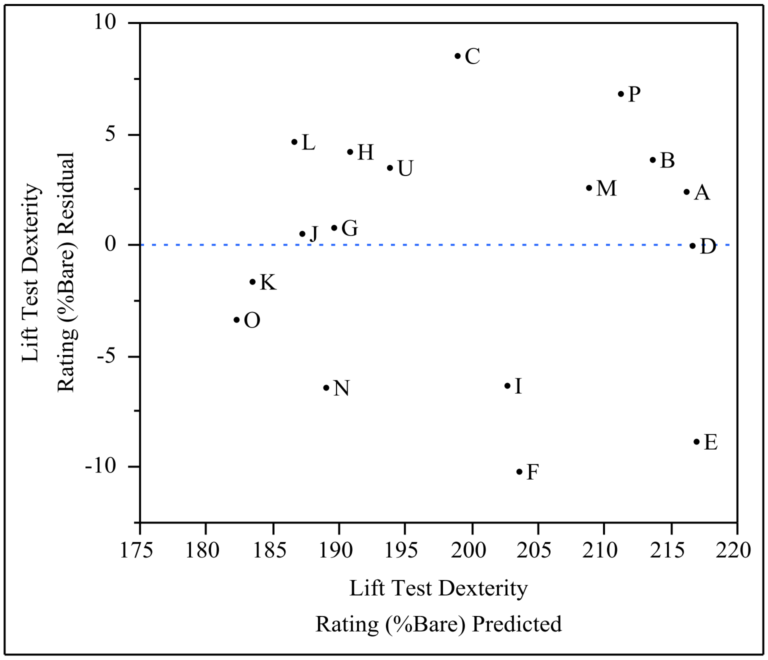


Figure B.1 Residual by Predicted Plot: Model 1

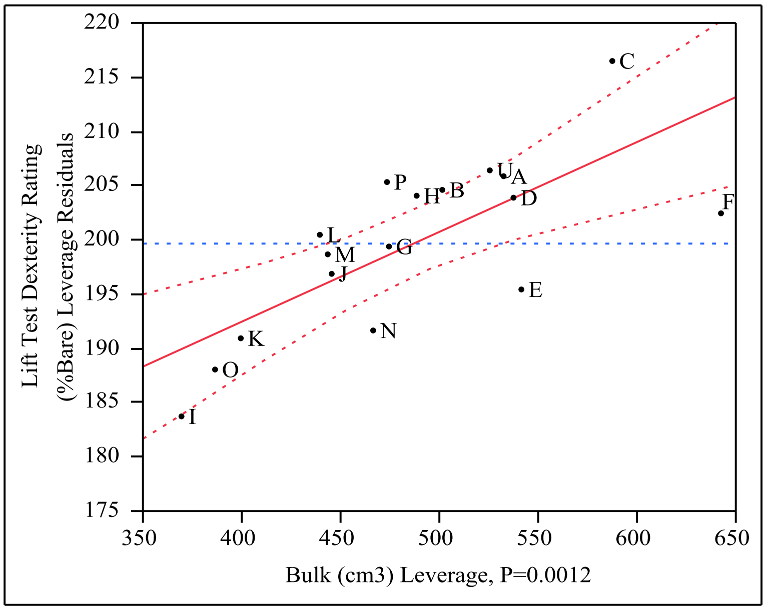


Figure B.2 Bulk Leverage Plot: Model 1

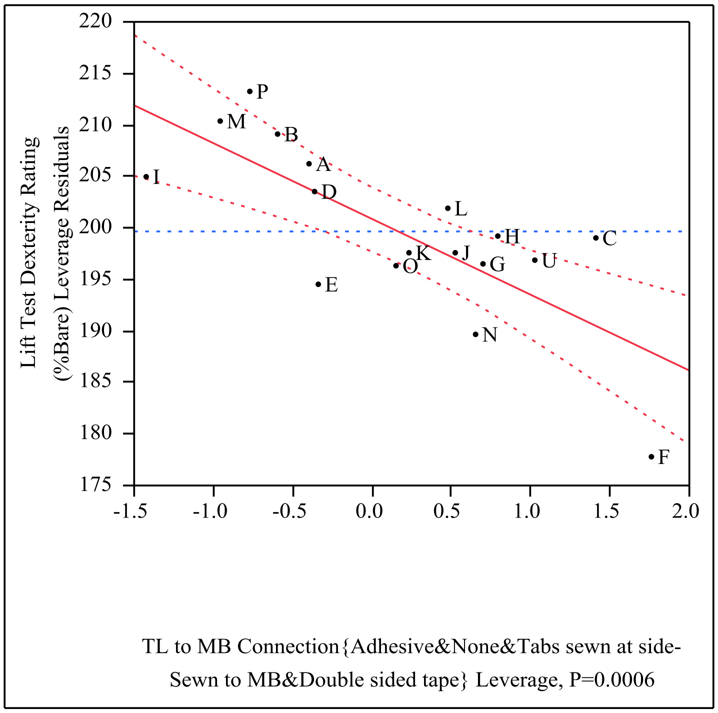


Figure B.3 TL to MB Connection{Adhesive&None&Tabs sewn at side-Sewn to MB&Double sided tape} Leverage Plot: Model 1

B.1.1 Analysis of Whole Glove Bulk

Model 2A

$$Whole\ Glove\ Bulk\ (cm3) = -1345.4 + 3.67 * Whole\ Glove\ Stiffness(lb) + 54.73 * Palm\ Composite\ Thickness(mm) + 13.16 * Thumb\ Circumference(mm)$$

Table B.5 Summary of Fit: Model 2A

RSquare	0.834369
RSquare Adj	0.801242
Root Mean Square Error	36.88518
Mean of Response	477.803
Observations (or Sum Wgts)	19

Table B.6 Analysis of Variance: Model 2A

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	102804.01	34268.0	25.1875
Error	15	20407.75	1360.5	**Prob > F**
C. Total	18	123211.75		<.0001*

Table B.7 Parameter Estimates: Model 2A

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1345.397	215.958	-6.23	<.0001*
Whole Glove Stiffness (lb)	3.6719279	0.801158	4.58	0.0004*
Palm Composite Thickness (mm)	54.731223	10.62399	5.15	0.0001*
Thumb Circumference (mm)	13.155435	1.580236	8.32	<.0001*

Table B.8 Effect Tests: Model 2A

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Whole Glove Stiffness (lb)	1	1	28579.596	21.0064	0.0004*
Palm Composite Thickness (mm)	1	1	36107.613	26.5396	0.0001*
Thumb Circumference (mm)	1	1	94290.970	69.3053	<.0001*

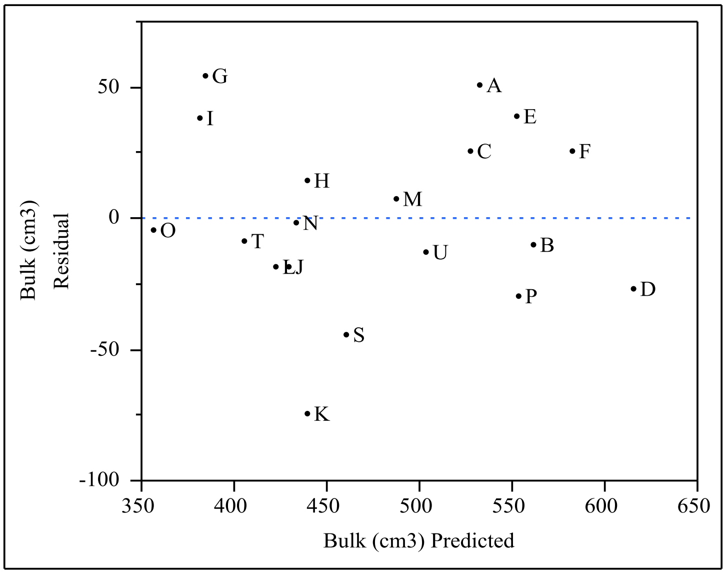


Figure B.4 Residual by Predicted Plot: Model 2A

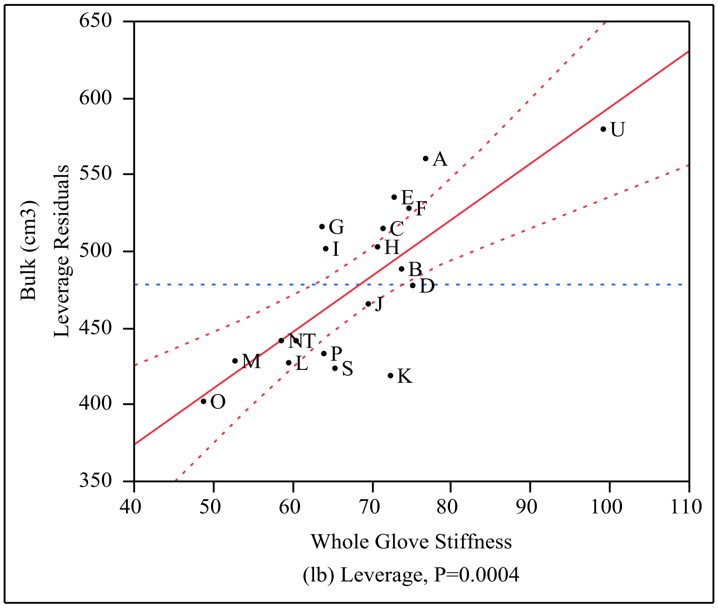


Figure B.5 Whole Glove Stiffness Leverage Plot: Model 2A

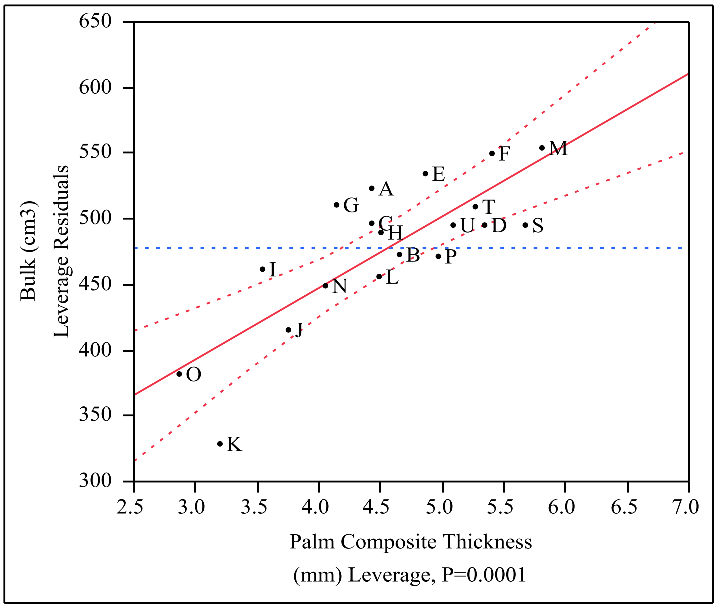


Figure B.6 Palm Composite Thickness Leverage Plot: Model 2A

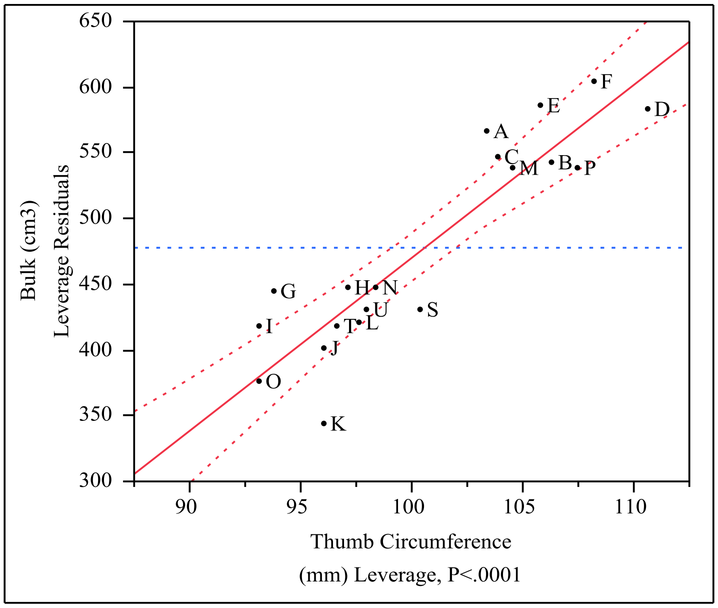


Figure B.7 Thumb Circumference Leverage Plot: Model 2A

B.1.2 Continued Analysis of Whole Glove Bulk

Model 2B

$$Whole\ Glove\ Bulk\ (cm3) = 486.5 - 55.05[Thumb\ Type\{Wing\ with\ Seam\ \&\ Wing - Straight\}]$$

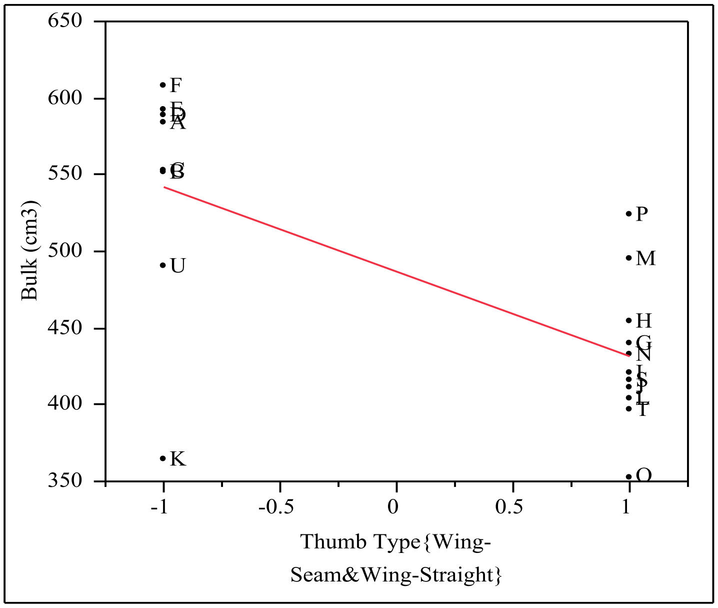


Figure B.8 Regression Plot: Model 2B

Table B.9 Summary of Fit: Model 2B

RSquare	0.455717
RSquare Adj	0.4237
Root Mean Square Error	62.80787
Mean of Response	477.803
Observations (or Sum Wgts)	19

Table B.10 Analysis of Variance: Model 2B

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	1	56149.67	56149.7	14.2337
Error	17	67062.08	3944.8	**Prob > F**
C. Total	18	123211.75		0.0015*

Table B.11 Parameter Estimates: Model 2B

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	486.49558	14.59216	33.34	<.0001*
Thumb Type{Wing-Seam&Wing-Straight}	-55.05276	14.59216	-3.77	0.0015*

Table B.12 Effect Tests: Model 2B

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Thumb Type{Wing-Seam&Wing-Straight}	1	1	56149.671	14.2337	0.0015*

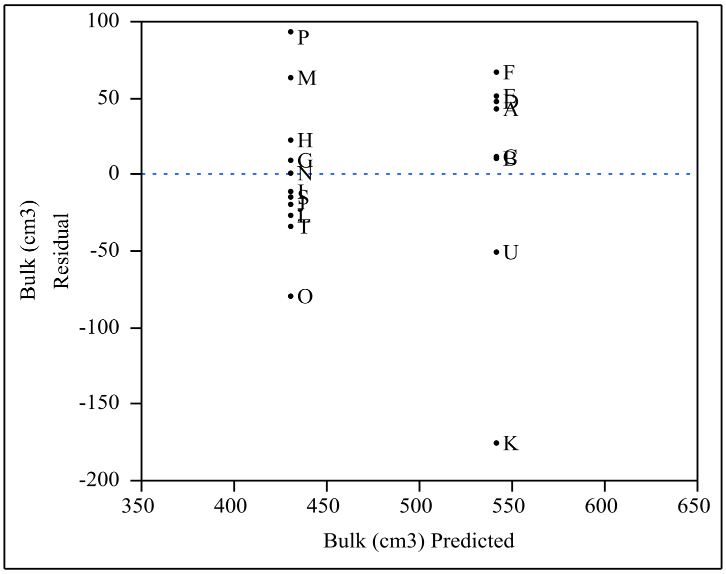


Figure B.9 Residual by Predicted Plot: Model 2B

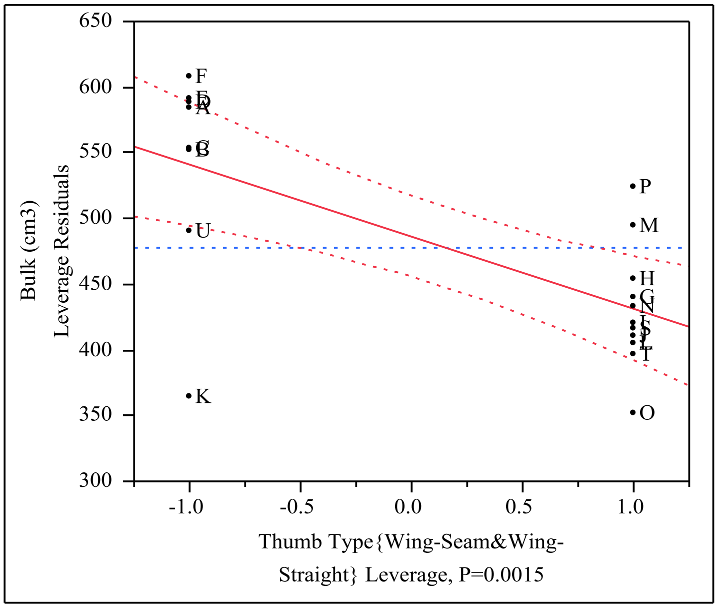


Figure B.10 Thumb Type{Wing-Seam&Wing-Straight} Leverage Plot: Model 2B

B.1.3 Analysis of Thumb Circumference

Model 3

$$Thumb\ Circumference\ (mm) = 98.13 + (Thumb\ Type)\begin{Bmatrix} Straight, 6.74 \\ Wing, 0.91 \\ Wing\ with\ Seam, -7.65 \end{Bmatrix}$$

Table B.13 Summary of Fit: Model 3

RSquare	0.377151
RSquare Adj	0.299295
Root Mean Square Error	6.200753
Mean of Response	100.5974
Observations (or Sum Wgts)	19

Table B.14 Analysis of Variance: Model 3

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	372.51290	186.256	4.8442
Error	16	615.18939	38.449	**Prob > F**
C. Total	18	987.70229		0.0226*

Table B.15 Parameter Estimates: Model 3

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	98.134693	1.773352	55.34	<.0001*
Thumb Type[Straight]	6.7395255	2.178722	3.09	0.0070*
Thumb Type[Wing]	0.9076678	2.137481	0.42	0.6768

Table B.16 Effect Tests: Model 3

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Thumb Type	2	2	372.51290	4.8442	0.0226*

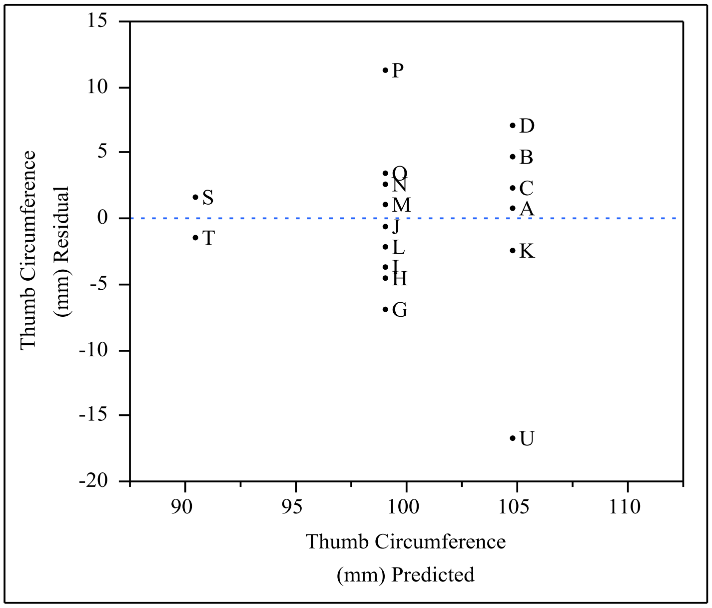


Figure B.11 Residual by Predicted Plot: Model 3

Table B.17 Least Squares Means Table: Model 3

Level	**Least Sq Mean**	**Std Error**	**Mean**
Straight	104.87422	2.1922972	104.874
Wing	99.04236	2.0669176	99.042
Wing-Seam	90.48750	4.3845945	90.488

B.1.4 Continued Analysis of Thumb Circumference

Model 4

$$Thumb\ Circumference\ (mm) = 99.11 - 5.67\ [TL\ to\ MB\ Connection\{Folded\ Rectangular\ Tab\ Sewn\ to\ Tip\ \&\ Tabs\ sewn\ at\ side\ \&\ Adhesive - Sewn\ to\ MB\ \&\ None\ \&\ Double\ Sided\ Tape\}]$$

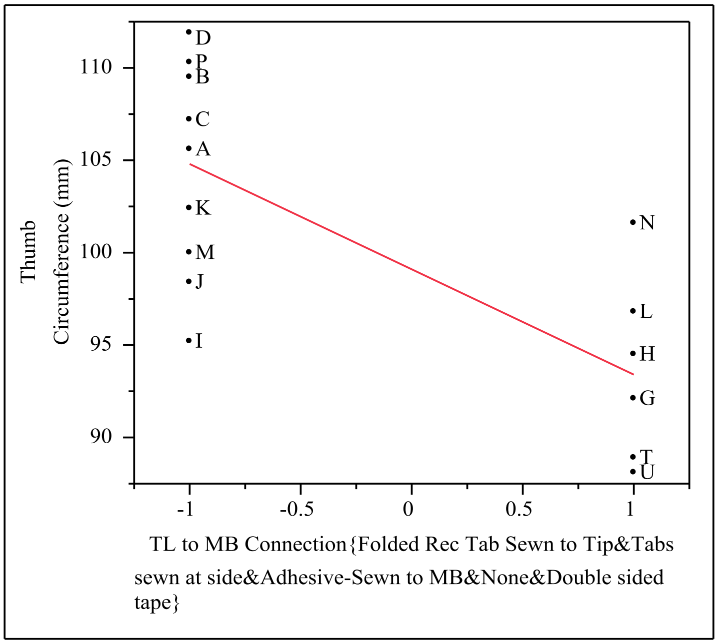


Figure B.12 Regression Plot: Model 4

Table B.18 Summary of Fit: Model 4

RSquare	0.575534
RSquare Adj	0.550565
Root Mean Square Error	4.966038
Mean of Response	100.5974
Observations (or Sum Wgts)	19

Table B.19 Analysis of Variance: Model 4

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	1	568.45630	568.456	23.0503
Error	17	419.24599	24.662	**Prob > F**
C. Total	18	987.70229		0.0002*

Table B.20 Parameter Estimates: Model 4

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	99.105357	1.180911	83.92	<.0001*
TL to MB Connection{Folded Rec Tab Sewn to Tip&Tabs sewn at side&Adhesive-Sewn to MB&None&Double sided tape}	-5.669643	1.180911	-4.80	0.0002*

Table B.21 Effect Tests: Model 4

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
TL to MB Connection{Folded Rec Tab Sewn to Tip&Tabs sewn at side&Adhesive-Sewn to MB&None&Double sided tape}	1	1	568.45630	23.0503	0.0002*

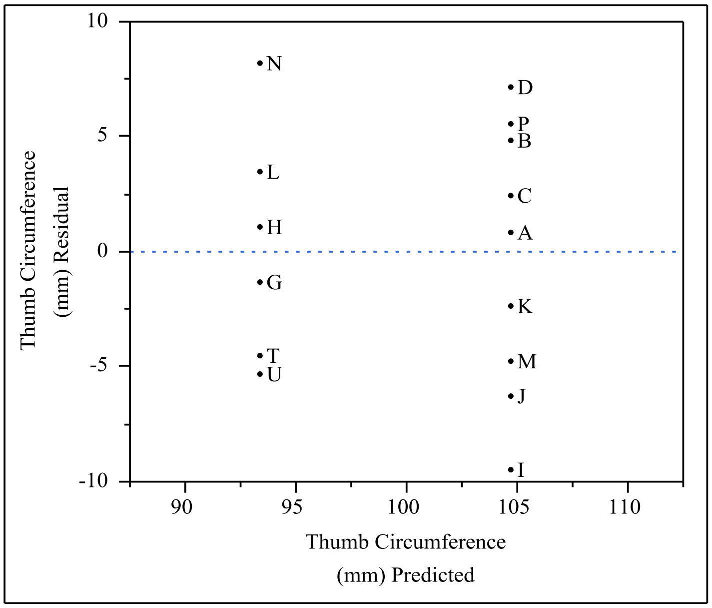


Figure B.13 Residual by Predictd Plot: Model 4

B.1.5 Analysis of Whole Glove Stiffness

Model 5

$$Whole\ Glove\ Stiffness\ (lb) = 65.41 - 4.05[Back\ Shell\{Synthetic\ \&\ Kangaroo\ \&\ Elk - Cow\}] + (Thumb\ Type)\begin{Bmatrix} Straight, 6.36 \\ Wing, -3.48 \\ Wing\ with\ Seam, -2.89 \end{Bmatrix}$$

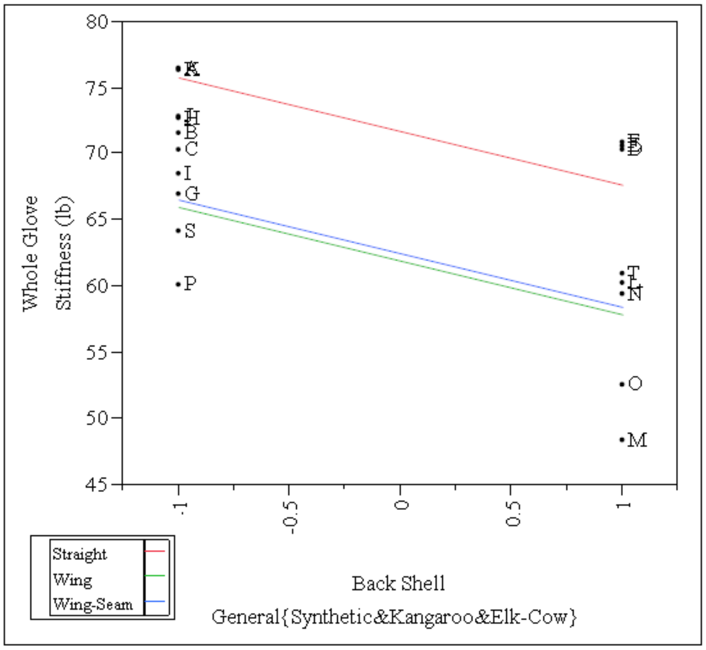


Figure B.14 Regression Plot: Model 5

Table B.22 Summary of Fit: Model 5

RSquare	0.672117
RSquare Adj	0.601856
Root Mean Square Error	4.988908
Mean of Response	66.27778
Observations (or Sum Wgts)	18

Table B.23 Analysis of Variance: Model 5

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	3	714.2736	238.091	9.5660
Error	14	348.4488	24.889	**Prob > F**
C. Total	17	1062.7224		0.0011*

Table B.24 Lack of Fit: Model 5

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	2	110.28792	55.1440	2.7785
Pure Error	12	238.16089	19.8467	**Prob > F**
Total Error	14	348.44880		0.1020
				Max RSq
				0.7759

Table B.25 Parameter Estimates: Model 5

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	65.411852	1.447455	45.19	<.0001*
Back Shell General{Synthetic&Kangaroo&Elk-Cow}	-4.052191	1.184281	-3.42	0.0041*
Thumb Type[Straight]	6.3628354	1.809703	3.52	0.0034*
Thumb Type[Wing]	-3.475984	1.734323	-2.00	0.0648

Table B.26 Effect Tests: Model 5

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Back Shell General{Synthetic&Kangaroo&Elk-Cow}	1	1	291.39437	11.7077	0.0041*
Thumb Type	2	2	405.46181	8.1453	0.0045*

B.2 Analysis of Dexterity: Tool Test

Table B.27 Partition Model Results for Tool Test Dexterity Rating

	RSquare	N	Number of Splits
Included	0.821	19	2
Excluded	0.307	5	

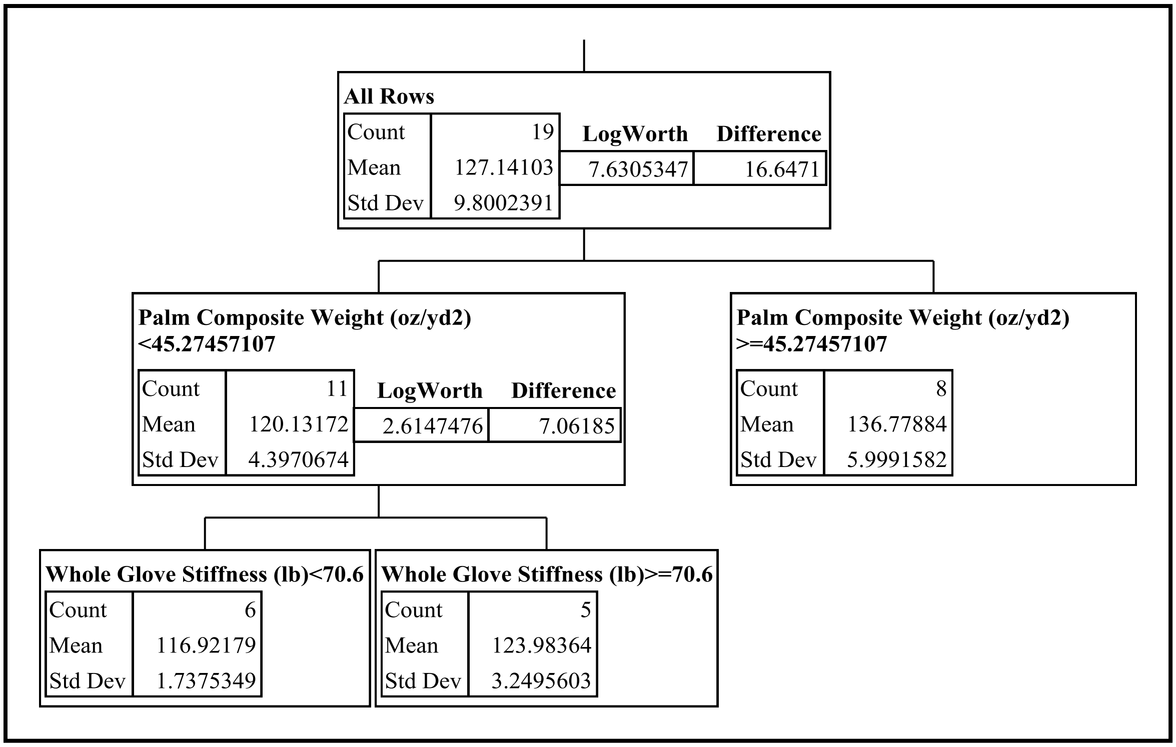


Figure B.15 Tree Diagram for Partition Model: Tool Test Dexterity

Table B.28 Leaf Report for Tool Test Dexterity Partition Model

Leaf Label	Mean	Count
Palm Composite Weight (oz/yd2)<45.27457107&Whole Glove Stiffness (lb)<70.6	116.921789	6
Palm Composite Weight (oz/yd2)<45.27457107&Whole Glove Stiffness (lb)>=70.6	123.983638	5
Palm Composite Weight (oz/yd2)>=45.27457107	136.778836	8

B.3 Continued Analysis of Dexterity: Tool Test

Equation 1 Model 6

$$
\begin{aligned}
&\mathit{Dexterity\ Performance} \\
&\quad = 199.9 - 0.77 * \mathit{Thumb\ Circumference}\ (mm) \\
&\quad - 3.38[\mathit{Back\ Shell}]\{\mathit{Kangaroo\ \&\ Elk - Cow}\} \\
&\quad + [\mathit{Moisture\ Barrier}]\left\{\begin{matrix} \mathit{Clear\ polyurethane}, 15.85 \\ \mathit{Crosstech}, 3.30 \\ \mathit{DirectGrip}, -0.12 \\ \mathit{RT}7100, -5.54 \\ \mathit{White\ Polyurethane}, -13.49 \end{matrix}\right\}
\end{aligned}
$$

Table B.29 Summary of Fit: Model 6

RSquare	0.889439
RSquare Adj	0.829133
Root Mean Square Error	4.086866
Mean of Response	127.5837
Observations (or Sum Wgts)	18

Table B.30 Analysis of Variance: Model 6

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	1478.0488	246.341	14.7488
Error	11	183.7272	16.702	**Prob > F**
C. Total	17	1661.7760		0.0001*

Table B.31 Parameter Estimates: Model 6

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	199.89585	17.30742	11.55	<.0001*
Thumb Circumference (mm)	-0.765413	0.172555	-4.44	0.0010*
Back Shell General{Kangaroo&Elk-Cow}	-3.375405	1.046314	-3.23	0.0081*
Moisure Barrier General[Clear Plastic]	15.845967	2.035436	7.79	<.0001*
Moisure Barrier General[Crosstech]	3.3039297	1.72157	1.92	0.0813
Moisure Barrier General[DirectGrip]	-0.118455	2.425577	-0.05	0.9619
Moisure Barrier General[RT7100]	-5.540079	3.453646	-1.60	0.1370

Table B.32 Effect Tests: Model 6

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Thumb Circumference (mm)	1	1	328.6380	19.6760	0.0010*
Back Shell General{Kangaroo&Elk-Cow}	1	1	173.8234	10.4070	0.0081*
Moisure Barrier General	4	4	1144.9660	17.1377	0.0001*

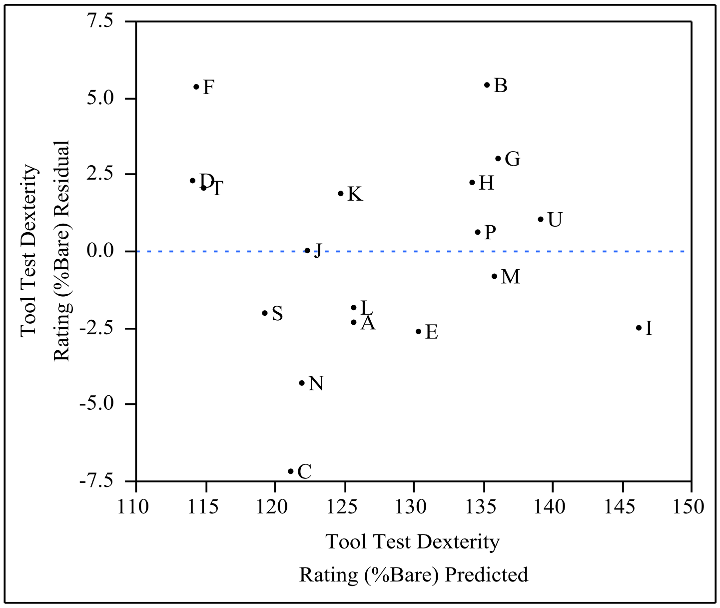


Figure B.16 Residual by Predicted Plot: Model 6

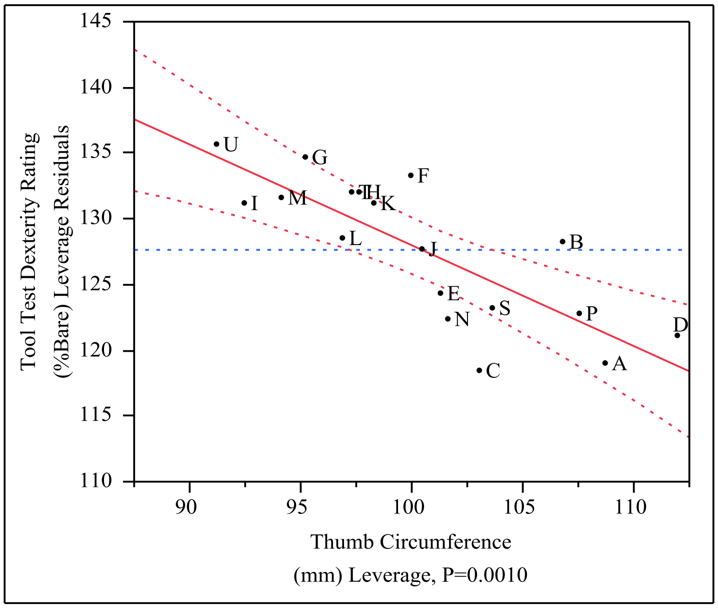


Figure B.17 Thumb Circumference Leverage Plot: Model 6

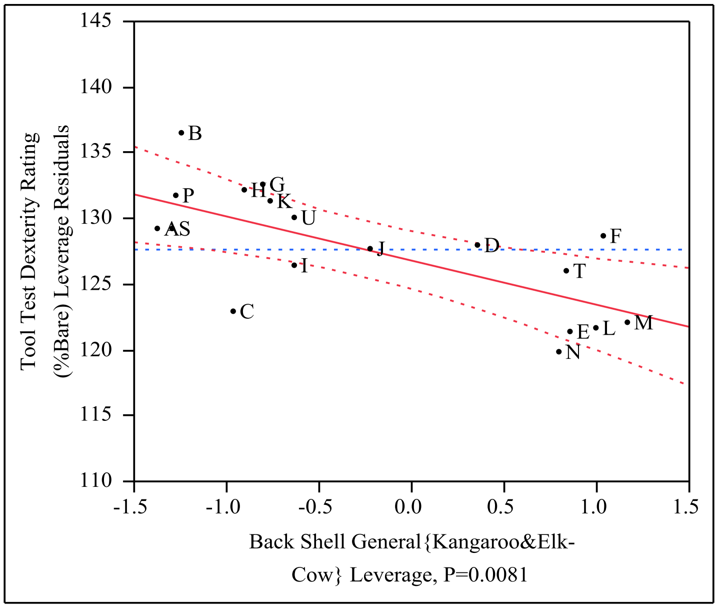


Figure B.18 Back Shell General{Kangaroo&Elk-Cow} Leverage Plot: Model 6

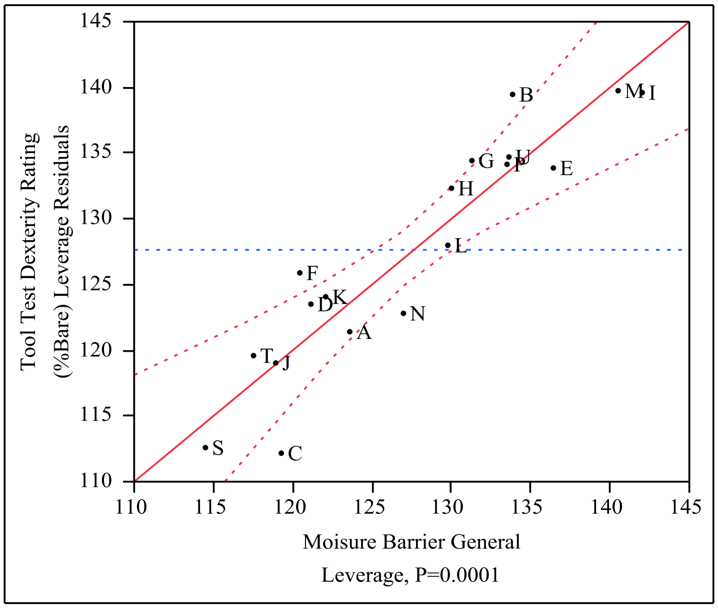


Figure B.19 Moisture Barrier Leverage Plot: Model 6

Table B.33 Least Squares Means: Model 6

Level	Least Sq Mean	Std Error	Mean
Clear Plastic	139.56975	1.9493120	136.464
Crosstech	127.02771	1.5836448	128.173
DirectGrip	123.60533	2.5295766	120.099
RT7100	118.18371	4.1645901	122.395
White Plastic	110.23242	3.4050265	117.144

B.4 Designing for Grip, As Measured by the Wet Torque Test

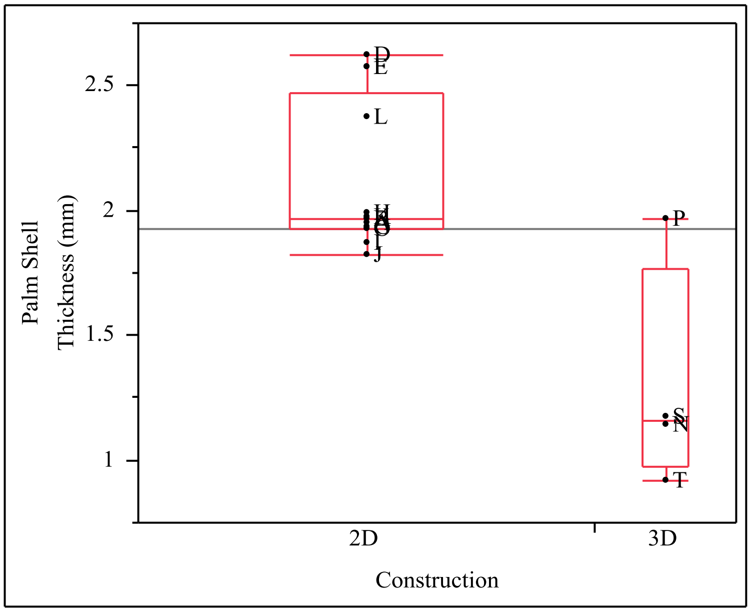


Figure B.20 Palm Shell Thickness by Construction (M and U Exclusion)

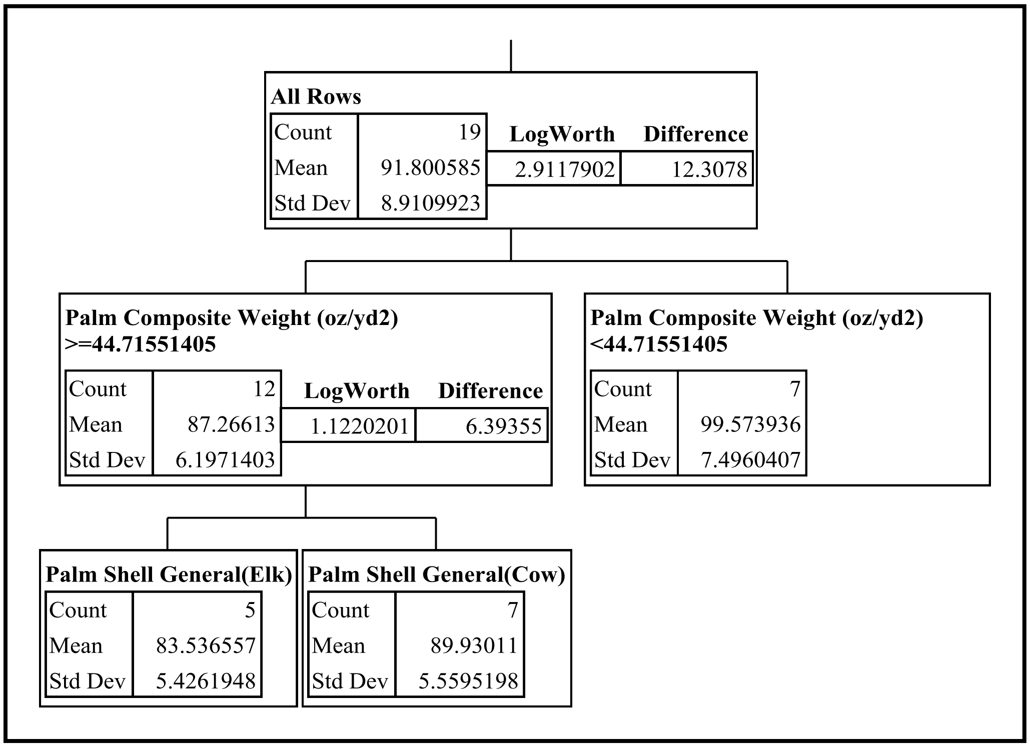
Table B.34 Connecting Letters Report Palm Shell Thickness by Constrction (M and U Exclusion) Student's t Test

Level			Mean
2D	A		2.1169231
3D		B	1.2986667

Levels not connected by same letter are significantly different.

Table B.35 Partition Model Results for Wet Torque Test Grip Rating

	RSquare	N	Number of Splits
Included	0.552	19	2
Excluded	-0.12	5	



Split 1	Reduction in Error SS = 784.29		Reduction in Error SS = 784.29
Split 2	Reduction in SS = 167.01	Reduction in SS = 167.01	

Figure B.21 Tree Diagram for Partition Model: Wet Torque Test

Table B.36 Leaf Report for Wet Torque Test Partition Model

Leaf Label	Mean	Count
Palm Composite Weight (oz/yd2)>=44.71551405&Palm Shell General(Elk)	83.5365572	5
Palm Composite Weight (oz/yd2)>=44.71551405&Palm Shell General(Cow)	89.9301105	7
Palm Composite Weight (oz/yd2)<44.71551405	99.5739361	7

Model 7

$$Grip\ Performance\ (Wet\ Torque\ Test) \\ = 113.01 - 10.63 * Palm\ Shell\ Thickness(mm)$$

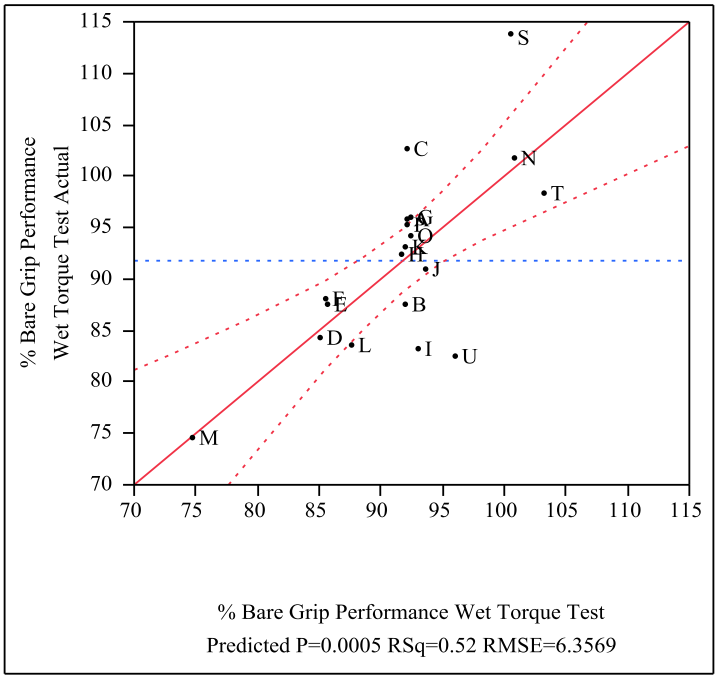


Figure B.22 Actual by Predicted Plot: Model 7

Table B.37 Summary of Fit: Model 7

RSquare	0.519363
RSquare Adj	0.49109
Root Mean Square Error	6.356919
Mean of Response	91.80058
Observations (or Sum Wgts)	19

Table B.38 Analysis of Variance: Model 7

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	1	742.3270	742.327	18.3697
Error	17	686.9771	40.410	**Prob > F**
C. Total	18	1429.3041		0.0005*

Table B.39 Parameter Estimates: Model 7

Term		Estimate	Std Error	t Ratio	Prob>|t|
Intercept		113.01274	5.159584	21.90	<.0001*
Palm Shell Thickness (mm)		-10.6349	2.481319	-4.29	0.0005*

Table B.40 Effect Tests: Model 7

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F	
Palm Shell Thickness (mm)	1	1	742.32699	18.3697	0.0005*	

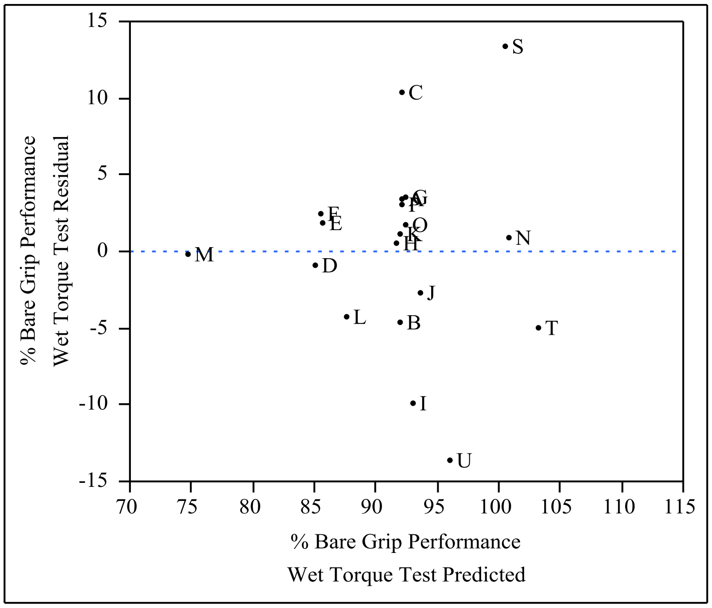


Figure B.23 Residual by Predicted Plot: Model 7

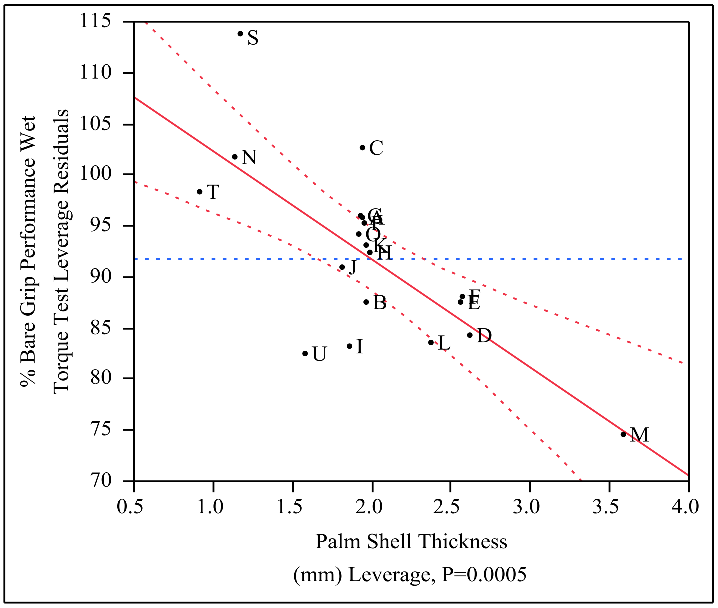


Figure B.24 Palm Shell Thickness Leverage Plot: Model 7

Model 8

$$
\begin{aligned}
&Grip\ Performance\ (Wet\ Torque\ Test)\\
&\quad = 92.69 - 8.75\\
&\quad * Palm\ Shell\{Elk\&Pigskin\&Cow - Kangaroo\&Digiroo\&Goat\} - 3.67\\
&\quad * Palm\ Shell\{Elk - Pigskin\&Cow\} - \ 6.92\\
&\quad * Palm\ Shell\{Kangaroo\&Digiroo - Goat\} - 5.44\\
&\quad * Number\ of\ Palm\ Layers\{4 - 3\&2\}
\end{aligned}
$$

Table B.41 Summary of Fit : Model 8

RSquare	0.813233
RSquare Adj	0.759871
Root Mean Square Error	4.366646
Mean of Response	91.80058
Observations (or Sum Wgts)	19

Table B.42 Analysis of Variance: Model 8

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	4	1162.3578	290.589	15.2400
Error	14	266.9463	19.068	**Prob > F**
C. Total	18	1429.3041		<.0001*

Table B.43 Parameter Estimates: Model 8

Term		**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept		92.693689	2.042312	45.39	<.0001*
Palm Shell General{Elk&Pigskin&Cow-Kangaroo&Digiroo&Goat}		-8.748501	1.480973	-5.91	<.0001*
Palm Shell General{Elk-Pigskin&Cow}		-3.674263	1.191607	-3.08	0.0081*
Palm Shell General{Kangaroo&Digiroo-Goat}		-6.924861	2.674013	-2.59	0.0214*
Number of Palm Layers{4-3&2}		-5.442721	1.670073	-3.26	0.0057*

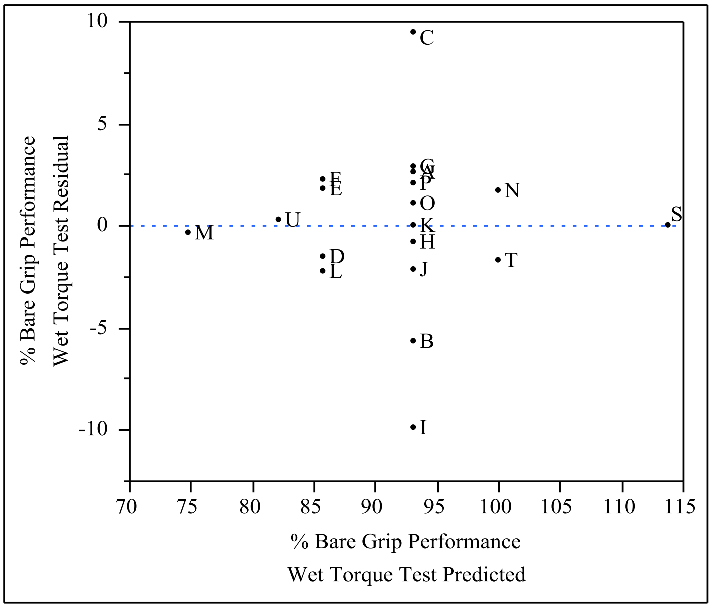


Figure B.25 Residual by Predicted Plot: Model 8

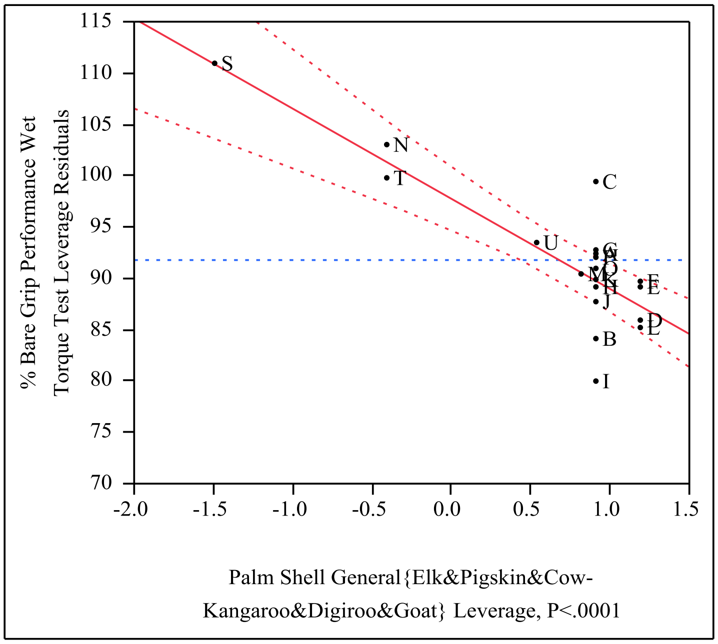


Figure B.26 Palm Shell General{Elk&Pigskin&Cow-Kangaroo&Digiroo&Goat} Leverage Plot: Model 8

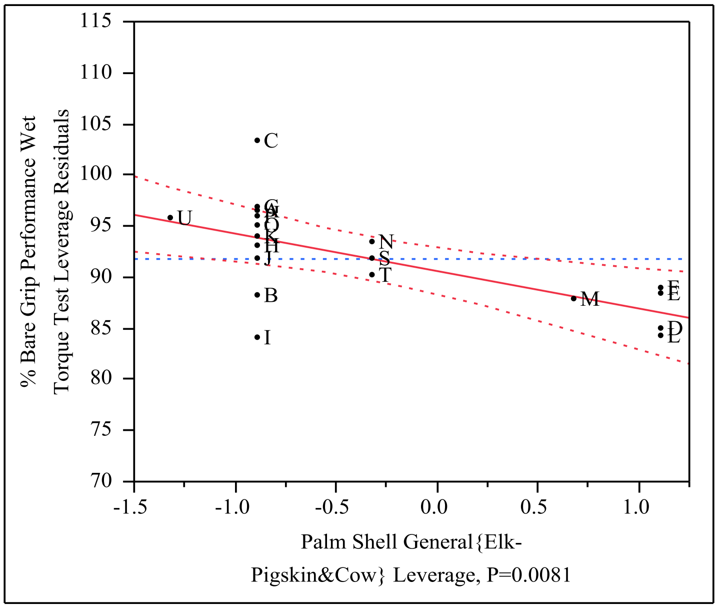


Figure B.27 Palm Shell General{Elk-Pigskin&Cow}Leverage Plot: Model 8

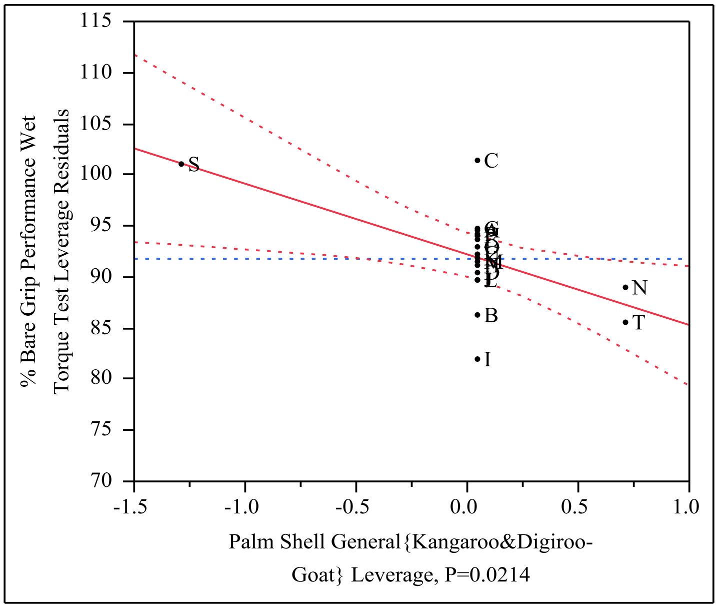


Figure B.28 Palm Shell General{Kangaroo&Digiroo-Goat} Leverage Plot: Model 8

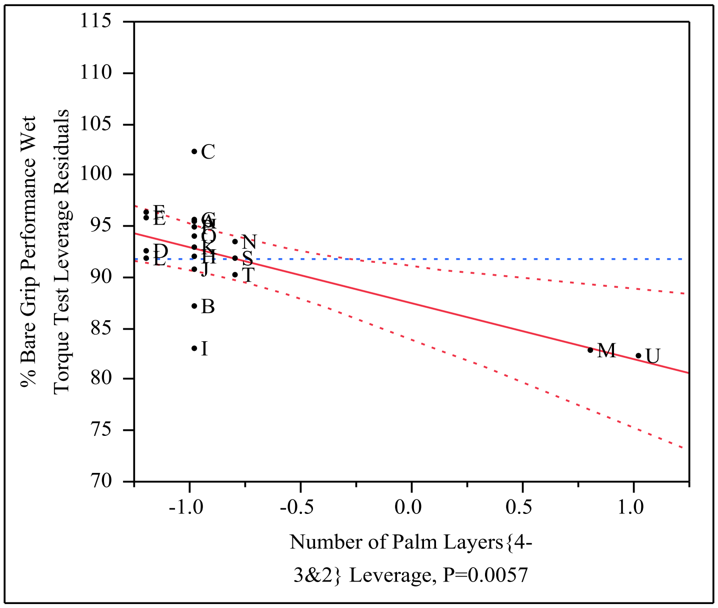


Figure B.29 Number of Palm Layers{4-3&2} Leverage Plot: Model 8

Appendix C – Statistical Methods

Forward selection stepwise regression was used to build the regression models for this research. This approach selects factors to add to the model that explains the chosen Y-variable at each step with a chosen alpha entry level (alpha = 0.05 for this research). Only factors that were significant at the 95% confidence level were included in the models [22].

The partition platform was also used to develop models for this research. The partition platform partitions data according to a relationship between the X (glove characteristics) and Y (grip or dexterity rating) values, creating a tree of partitions. It finds a set of groupings of X values that best predict a Y value. It searches all the factors and finds the optimum split in the data for the factor that best reduces the change in the squared errors due to the split. It continues in this way until no further splits (partitions) can be made [22]. The final result is a certain number of groupings or categories of the Y-value based on X-criteria. The Y-values are plotted in the groups in which they appear with a regression line drawn through the averages of each group. In this way, an R^2 value can be calculated to evaluate the quality of the model.

In some cases, the strength of a relationship between two sets of data was valuable information. Both the Pearson product-moment correlation coefficient and Spearman's Rho were tools used in this study. The Pearson product-moment correlation coefficient measures the strength of the linear relationship between two variables. For response variables X and Y, it is denoted as r. If there is an exact linear relationship between two variables, the correlation is 1 or -1, depending on whether the variables are positively or negatively related.

If there is no linear relationship, the correlation tends toward zero [22]. For the Spearman correlations, the data are first ranked. Computations are then performed on the ranks of the data values. Average ranks are used in case of ties [22].

To determine the discriminating power of the different test methods, a collection of Student’s t tests were conducted to build a connected letters report showing differences between gloves grip and dexterity performance [22].