ABSTRACT

DORAN, ERIN BROOKE. The Integration of Flatbed Spacer Knit Fabric into Athletic Apparel and the Effect on Perceived User Comfort. (Under the direction of Dr. Andre West).

The purpose of this study was to discern whether flatbed weft knit spacer fabrics increased user comfort in athletic applications when used as padding. In order to test these fabrics, rock climbers wore pants enhanced with spacer fabric padding in the specific areas where the harnesses put pressure on the body. Two different spacer knit fabrics were produced on a flatbed weft knit machine. The first was a full panel of spacer knit, and the second comprised of a half jersey and half spacer knit structure. These two fabrics were tested against a base layer fabric.

In this study, physical tests were conducted to determine fabric hand and strength while basic measurements were taken of these three fabrics. Physical tests include fabric compression, surface roughness, thickness, weight, and bursting strength. These tests accompanied garment level testing conducted through wear trials. For the wear trials, the fabrics were then sewn into pre-existing base layer garments before they were worn by 10 volunteer rock climbers.

Results of the wear trials concluded that participants preferred both spacer knit fabrics over the standard base layer fabric because they offered additional sensory comfort without affecting garment performance. Additional user responses and physical test results established that the full spacer fabric provided the most comfort, while the half spacer fabric provided a material that was characteristically similar to the base layer fabric.

The Integration of Flatbed Spacer Knit Fabric into Athletic Apparel and the Effect on Perceived User Comfort

by

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DEDICATION

This thesis is dedicated to Alex Razzolini. I will be forever grateful that your light touched my life and added a little razzle dazzle to it. We all are.

BIOGRAPHY

Erin Doran was born in Winston-Salem, NC in 1993. As the second child to Susan and Tim Doran, she could usually be found trailing behind her older sister, Hana. Since those early days, she has traveled a few places on this planet but always seems to come back to NC much to the satisfaction of her parents.

After accidentally signing up for a College of Textile tour when visiting NC State, Erin discovered a world where she could blend her scientific and artistic interests in textiles. She received her undergraduate degree from NC State University in May of 2015 with a major in fashion and textile design with a concentration in textile design and a minor in outdoor leadership. While pursuing her master's degree, Erin was the first graduate assistant to work in the College of Textiles Knitting Lab managed by James Brian Davis.

After having a wide range of jobs, from horse trek guide to a repair intern for Patagonia, Erin is an outdoor textile enthusiast. She tries to be a steward to the environment and an advocate for sustainable textile processes. A lover of any outdoor activity, namely rock climbing, Erin is excited to graduate and find a way to bring her love of the wilderness and adventure into work every day.

ACKNOWLEDGEMENTS

I would first like to acknowledge my thesis committee, who helped make this research possible. It was Dr. Andre West who first convinced me to get my master's degree, and as my committee chair has helped me through this journey. Nancy Powell has taught and supported me through my undergraduate and graduate studies. It was a pleasure, as always, to work with her one last time at NC State on my thesis committee. Dr. Kate Annett-Hitchcock was very helpful in bringing balance to the project. I thank you all.

Throughout my time at the College of Textiles, I have had the support and encouragement of all the faculty and staff. I would not be the designer I am today without all the resources and doors they helped me open. This especially includes Brian Davis, my boss and friend, who taught me how to use and understand the technology that made this project a reality. Thank you for sharing your lab, Dr. Peppers, and knowledge when helping me through all my Knit Assist and machine errors.

I would also like to acknowledge my high school history teacher, Allen Smith, who taught me that you are exactly who you are supposed to be. My college teachers, mentors, and friends in outdoor pursuits, namely Terry Dash and Scott Schneider. These two men helped shape the woman I have become. I can always count on them for a belay, gear idea, advice, and laughs.

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INTRODUCTION

Comfort comes in many forms and is a part of daily life. From clothing to cars, comfort is at the forefront of the concerns of both consumers and designers. It was in the pursuit of comfort that spacer fabrics were invented. A three-dimensional fabric that often replaces polyurethane foam as padding, spacer knit fabric can be found in many household objects, from swimsuits to backpacks. Existing studies into spacer fabrics showed their industrial uses in automotive and mattress cushioning as well as their capabilities in sound resilience. The current study was designed to test the use of spacer fabrics as skin-level comfort padding in an athletic apparel application. Two different kinds of spacer fabric were produced, compared to traditional base layer fabrics, and tested in garment form.

Background of the Problem

This research began with an investigation into the growing market of athletic apparel and sportswear. Venkatraman and Hayes (2016) conceded that sportswear “is about functionality, comfort, and safety with the specification developed and designed to deliver a product that fits the needs of the sportsman” (p. 2). Clothing functionality is dependent upon the specific activity, environmental conditions, and level of exertion (Ozdil & Anand, 2014). Comfort can be measured in a variety of ways. This study focused on sensory and body movement comfort in clothing. Sensory comfort refers to the interaction between textiles and skin while body movement comfort concerns the freedom of motion in a garment (Song, 2011). Finally, sportswear also includes elements of safety. Padding is the aspect of clothing safety that was the focus in this study, specifically padding that is meant for cushioning comfort. As Fung (2005) stated, “Comfort is not only essential for enjoyment, but also important for safety, because in potentially dangerous sports . . . good judgement can be influenced by discomfort” (p. 135). Different kinds of cushioning in sportswear include foams, neoprene, and spacer knit fabrics (Pererira, Anand, Rajendran, & Wood, 2007).

Spacer knit fabrics can be produced using a warp or weft knitting machine. From cushioning applications to compression testing, research into warp knit spacer fabric overshadows the research into weft knit spacer fabrics. As Liu and Hu (2011) stated in their investigation of the lesser researched spacer fabric type, “In the recent years, great attention has been paid to weft-knitted spacer fabrics due to their good transversal compressibility and excellent air permeability . . . [but] the properties of the weft-knitted spacer fabrics are still not clearly established” (p. 366). Within weft knitting, there are flatbed and circular knit machines that can produce spacer knit fabrics. While there are some studies into circular knit spacer fabric in both intimate apparel applications (Yip & Ng, 2008) and its use in knee braces (Pererira et al., 2007), there is little research into the uses and applications of flatbed spacer knit fabrics.

With new advancements in knitting technologies, flatbed knitting machines have the ability to knit complex stitches into a tube. This allows knit structures, including spacer fabrics, to be added into a completely seamless garment. The machines capable of producing seamless garments are in a developing market, meaning they are not widely used in garment production at this time. Venkatraman and Hayes (2016) discussed that there is “a need for companies to invest in research and development in order to improve knowledge and understanding and truly exploit the potential capabilities of seamless knitting technologies” (p. 243). The current research was designed to contribute to the current knowledge base through further exploration into the possibilities of flatbed spacer fabrics in seamless sportswear.

Purpose of the Study

The purpose of this pilot research was to explore the use of flatbed spacer knit fabrics in base layer garments for sportswear. A base layer is the “innermost garment in a layering system which is, apart from underwear, closest to the skin” (Haffenden & Smith, 2014, p. 1). This type of garment was used in this study because its allows additional padding to be close to the body, thereby reducing the likelihood of padding movement. This study included an examination of how different knit structures of spacer fabrics compared to a base layer fabric. Spacer fabrics were also incorporated into garments and tested to gather user feedback. The research objectives were as follows:

1. Investigate the differences in sensory comfort between spacer knit fabrics and commercially available base layer fabric.
2. Determine whether spacer knit fabrics can be an effective padding used to increase user comfort without affecting garment performance.
3. Determine whether different knit structures combined with spacer fabrics affect user comfort.

Primary Research Questions

With the above objectives in mind, the subsequent research questions were developed alongside the research design.

1. What are the differences and similarities in fabric hand between the spacer fabrics created and base layer fabrics?
2. When used by rock climbers, do these spacer knit fabrics increase user comfort without affecting garment performance?
3. Which of the three pants tested do participants believe performed better for rock climbing applications, and why?

Research Design

First, fabric testing was performed to achieve quantitative data. These findings were intended to better understand the effect of knit structures, specifically spacer knit structure, on fabric hand variables. These rounds of fabric testing also provided usable information about the specific differences between the two spacer fabrics that were created for testing in this study.

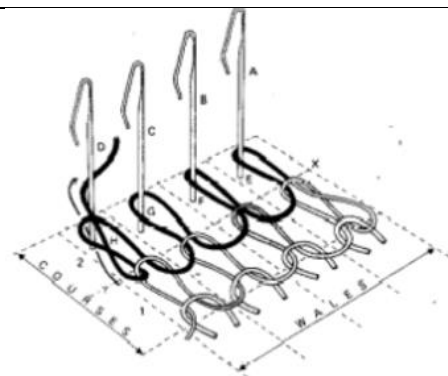
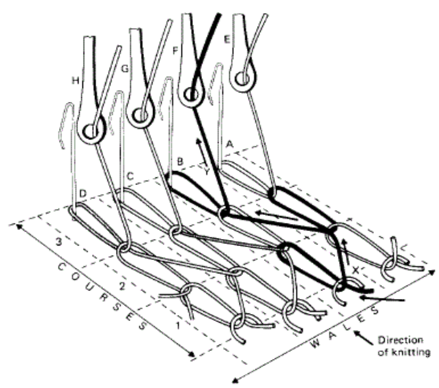
To test the effectiveness of spacer fabrics in weighted applications, a specific testing environment had to be identified. Because of the fully weighted, hanging nature of certain positions of climbers, rock climbing was the case study chosen for this study. Rock climbing uses a variety of muscle groups, movements, and weighted scenarios that enabled users to give useful feedback on the differences between pants with and without spacer fabric padding. For the wear testing trials, two different spacer knit fabrics were sewn into pairs of close fitting pants to pad the areas of the body on which pressure is exerted while climbing. These two pairs of pants with spacer padding were compared against a control pant with no padding.

LITERATURE REVIEW

Overview of Knitting Methods

Knitted fabrics fall into two different categories—warp or weft knits—that are dependent on the fabric production method. Weft knit fabric is created in rows of loops in a horizontal direction across the width of the fabric. Warp knit fabric is created in columns, with loops that zig-zag vertically along the length of the fabric. Table 1 shows the characteristics and illustrations of the two knit production methods.

Table 1.
Weft and Warp Knit Characteristics (Spencer, 2001, pp. 48-49)

Type	Characteristics	Illustration
Weft Knit	• Needle beds are circular or straight • Fabric is produced in the horizontal direction • Each end of yarn is fed into a machine via a yarn carrier	
Warp Knit	• Needle beds are rectangular or straight • Fabric is produced in the vertical direction • Each end of the yarn is drawn through one guide on guide bars	

Weft knit machines derived from early hand knitting, which is considered weft knitting. The first knitting machines created were weft knit frames made for stocking production in the late 1500s in Europe. In 1750, products made on weft knitting machines were finally considered to be equal in quality to hand produced products. Warp knitting was developed in 1769 and has always been a machine powered production method (Spencer, 2001).

Even with the technological advances that have occurred over the last 500 years, from hand to computerized machine knitting, the basic terms and principles of knitting have remained the same. A *knit* stitch is one loop of yarn. These loops are interlocked with other loops to create a knitted fabric as shown in Table 1. The term *wale* describes a column of knit stitches and the term *course* describes a row of knit stitches. By counting the wales and courses of a fabric in a given area, the *stitch density*, a measure of the knit stitches in an area, can be determined. *Stitch length* (usually given in mm) is the length of yarn it takes to create one loop in a knit fabric.

Both of these measurements are related to the machine's *gauge*, which is the number of needles in a given measurement, usually stated in needles per inch (Spencer, 2001). The gauge of the machine is related to the size of yarn that can be knitted on the machine. The machine's needle size dictates the size of yarn it is able to grasp to create a knitted loop. For example, one end of yarn used on a 3-gauge machine will be larger than one end of yarn used on a 15-gauge machine. Another machine characteristic that affects fabric production is stitch cams. *Stitch cams* are simply the part of the machine that moves the needles and thus controls the complexity of the knit designs capable of production on that machine. The tension on the fabric being produced and the amount of yarn being delivered or fed into the machine can also affect the end weight of the fabric. Fabric weight, knit structure, and the yarn used then determine the end usage and application of the fabric (Spencer, 2001).

As previously discussed, knit fabrics are either weft or warp knit. In both production methods, machines can have either one or two needle beds. In warp knitting, yarn is delivered to the machine by guide bars that move around the needle beds in a swing-like motion to create knit stitches. Knit structures in warp knitting are determined by the pattern of movement of the yarns around the needles. In order for this guide bar movement to knit successfully, the yarns require constant tension to not over feed into the machine. This mandatory tension means the yarns used in warp knitting must be strong enough to resist or avoid breaking under tension but have enough stretch to bend around the needles when creating loops. Thus, the types of yarn that can be knit on warp machines are much more limited than those used on weft machines.

In weft knitting, the needles of the machine are moving while the yarn stays in a fixed position. The needles use stitch cams to move up and down in the machine to grab the yarn that is being delivered. The position of the stitch cams cause the needles to move and thus determine the knit structure. Typical fibers used in apparel like cotton and wool, which are relatively weak, are knitted on weft machines, while monofilament yarns and other strong synthetic yarns, which can be under greater tension, are traditionally used on warp machines (Spencer, 2001).

Weft knit fabrics can be created on circular or straight needle beds. Machines with circular beds are referred to as circular machines and can have one or two needle beds (Spencer, 2001). Figure 1 illustrates the different needle bed layouts of double and single jersey knit machines. Single jersey knit machines have one vertical bed of needles called the cylinder, which produces one layer of knit fabric with a definitive front and back side called the technical front and technical back. The double jersey knit machine ("double-knit") has two perpendicular needle beds, called the cylinder and dial. This needle bed layout creates a fabric with two layers knitted together. The fabric will look like it has two technical front sides instead of a technical front and a technical back (Spencer, 2001).

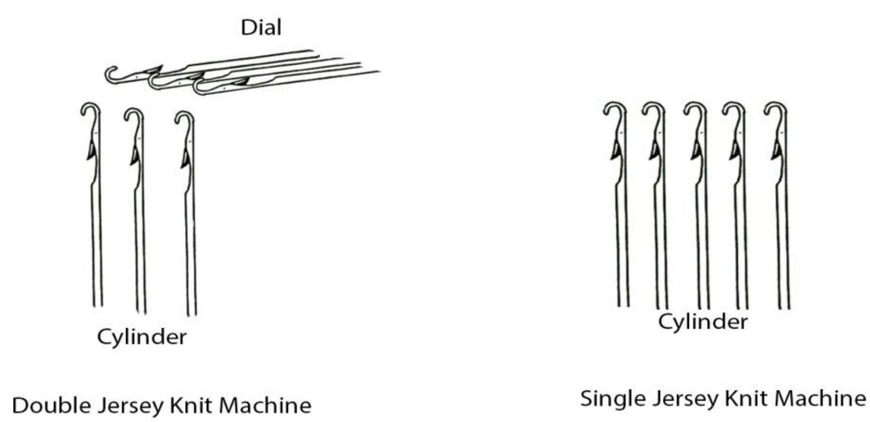


Figure 1. Double and single jersey knit machine needle bed layout.

Circular knitting machines are used to manufacture large quantities of fabric because many yarn feeders can be stationed around the machine. This means fabric can be created quickly as the machine knits a multitude of yarns simultaneously around the circular needle beds (Spencer, 2001).

Straight needle bed weft knit machines are referred to as flatbed or v-beds. This type of knit machine got its name because of the machine set up, where two beds of needles mirror each other in an inverted “v” shape. These weft knit machines are often used for coarser or lower gauge products, like sweaters. Flatbed machines can produce complex stitch patterns, such as traditional cable stitches, because they can move the stitches further in the horizontal direction than circular knit machines. This horizontal movement occurs when machine racking or stitches are transferred. *Machine racking* refers to a needle bed moving laterally on the machine. *Stitch transferring* involves taking a stitch off its needle and moving it to an adjacent needle. Instead of having continuous feeders all around the circumference of the machine as in circular knitting, yarns are moved across the needle beds in individual carriers. These carriers are controlled by a carriage that pushes the carriers across the bed to deliver yarn to the needles. Inside the carriage, the stitch cams control the needle movements that develop different knit structures. In computerized flatbed knitting, individually controlled yarn carriers can move themselves across the needle bed. Because fewer yarns are being fed into the machine and the yarns must pause at each end of the needle bed in order to go back and forth across the machine, flatbed knitting is a slower method of fabric production than circular knitting, which knits continuously (Spencer, 2001).

As researchers have begun to explore the possible uses of fabrics in applications outside of traditional apparel, knit fabrics have expanded into medical and industrial markets. Between 1977 and 1988, researchers found ways to create a type of three-dimensional knit fabric, what would later be called spacer fabric, on both warp and circular machines (Sato & Furuya, 1988).

Spacer Fabric Construction and Applications

A knitted spacer fabric is a three-dimensional textile construction consisting of three connected layers: bottom, top, and spacer layer. The spacer layer connects the top and bottom layers and creates loft between them (Liu & Hu, 2011). Knitted spacer fabrics can be created through warp or weft knitting (Dias, Monaragala, Needham, & Lay, 2007). This knit structure can help fabric transfer moisture and heat through the structure, improving user comfort. As research has shown, comfort is a contributing factor in why consumers buy a product (Duru & Candan, 2013). Because of the breathability of spacer fabrics, they do not retain as much moisture as comparable materials like neoprene, polyurethane, and other foam-based cushioning and protective layers. This breathability is attributed to the negative space created by the spacer layer between the top and bottom layers, as shown in Figure 2. This breathability makes spacer knit fabrics an alternative choice for cushioning and padding applications (Yip & Ng, 2008). As Gokarneshan (2015) wrote, “Spacer fabrics can be used as a type of effective material . . . for human body protection like shoulder protectors and back protectors in sports and related applications” (p. 6). This indicates spacer fabrics may eventually replace foam and other padding materials to improve consumer comfort and reduce the environmental impact. Spacer fabrics are also recyclable, unlike foam padding, which is an advantage as environmental responsibility is becoming increasingly important (Gokarneshan, 2015; Liu & Hu, 2011).

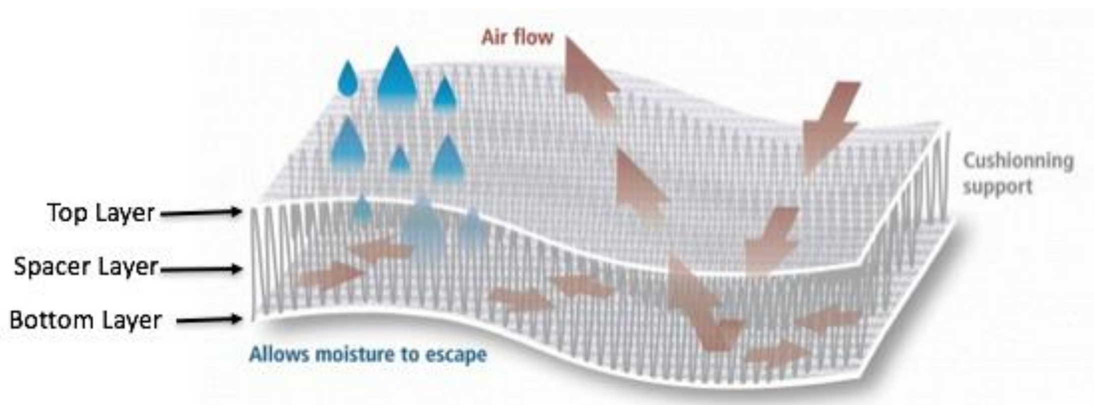


Figure 2. Breathability and moisture transfer of spacer fabric (Davimed Supplies, n.d.).

Warp knit spacer fabrics. Warp knit spacer fabrics are manufactured using a double needle bar, rib Raschel machine, as shown in Figure 3. The setup of this two needle bar machine, with at least three guide bars, allows the outside yarns on each guide bar to knit the top and bottom foundation fabrics, while the middle yarns create the spacer layer between these two layers. However, as can be seen in Figure 3, spacer warps usually have five guide bars, one for the spacer layer and two each for the bottom and top layers (Yip & Ng, 2008). This spacer layer is created by swinging the middle guide bars around the outside needle bars, effectively tucking the spacer yarn behind the top and bottom layers (He, 2011). The distance between the two outside needle beds on the machine determines the thickness of the spacer fabric created.

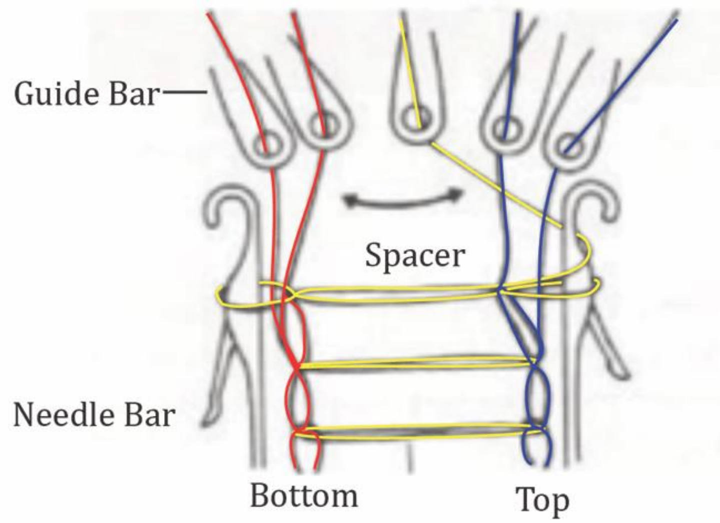


Figure 3. Spacer fabric illustration on double needle bar, warp knit machine (Spencer, 2001, p. 368).

This production method is used in technical textile applications that can replace the foam or other cushioning materials used in products like mattresses and car seats. This type of spacer fabric is used because of its compression resiliency (Gokarneshan, 2015). With warp knitting, the structure of the spacer yarn within the knit pattern can be easily controlled by changing the way the yarns move behind the needle bars. This method allows for the production of a wide range of fabric structures and thicknesses (He, 2011). However, because of the tension exerted on the yarn during warp knitting, the yarn strength requirement limits the types of yarn that can be warp knit (Spencer, 2001).

Circular weft knit spacer fabric. Weft spacer knit fabrics are being produced on double needle bed machines that use circular knitting, which are referred to as double face jersey machines. Though circular machines have been used more predominately to create spacer knits, recent technological advances related to easing the transfer of yarns between weft knit flatbeds have made it possible to create spacer fabrics on flatbed machines (Liu & Hu, 2011). Between the two weft knit spacer manufacturing methods, double face jersey machines more quickly and efficiently produce spacer fabric than flatbed machines (Yip & Ng, 2008). A circular knit machine has a dial and a cylinder that sit perpendicular to each other on the double knit machines, as shown earlier in Figures 1 and 5. Double knit fabrics are made possible by these perpendicular needle beds, as the cylinder knits the front layer of fabric and the dial knits the back of the fabric. Spacer fabric is created when a separate yarn is tucked between these two fabric faces, as shown in Figures 4 and 5, both in knit notation and diagram.

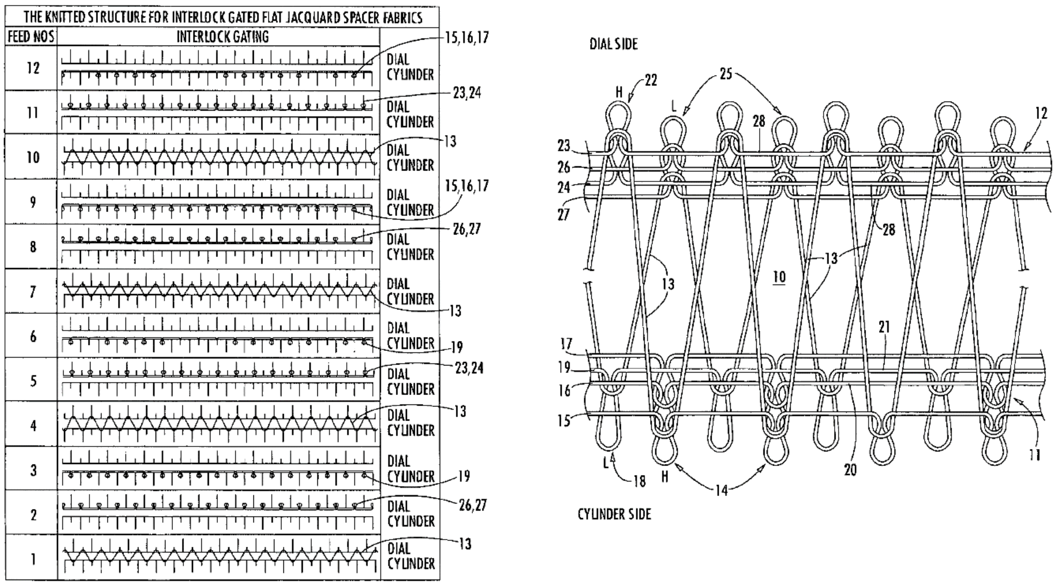


Figure 4. Knit notation and illustration of circular weft knit spacer fabric produced on double jersey machine (Shepherd, 2004, p. 1).

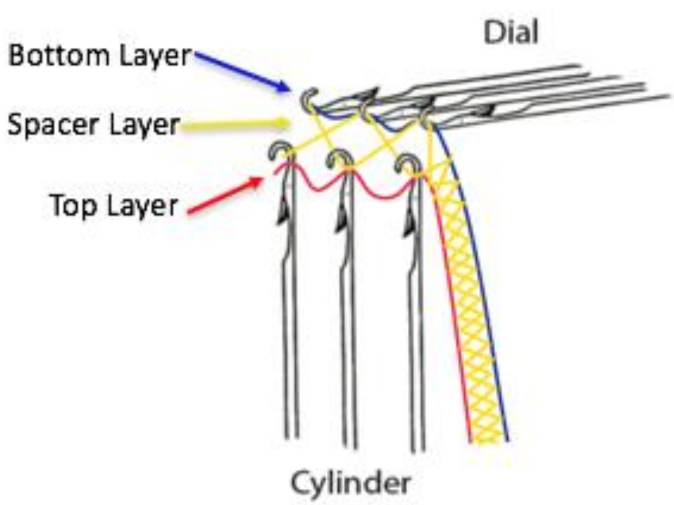


Figure 5. Example of circular spacer knit fabric on double jersey machine.

The distance between the dial and cylinder controls the spacer fabric thickness (Yip & Ng, 2008). By moving the dial and cylinder further away from each other on the machine, the space between the top and bottom knit layers becomes greater. The spacer yarn must travel a greater distance to tuck between the two faces, making a thicker spacer fabric.

Flatbed weft knit spacer fabric. Where spacer fabric on a double knit circular machine incorporates both the dial and cylinder needle beds, as shown in Figures 4 and 5, the flatbed spacer fabrics use the mirrored front and back needle beds to tuck the spacer yarn between the fabric faces. With machine programming, variations in spacer fabric thickness can be easily controlled by altering the distance between tucks on the inside of the needle beds. For example, the spacer yarn can be tucked every fourth needle between the bottom and top layers, and the number of needles between tucks can be increased to increase spacer fabric thickness. This means a fabric with the spacer yarn tucked every fourth needle is thinner than a fabric with the spacer yarn tucked every eight needles because more yarn is being added between the top and bottom layers in the latter fabric (Ionesi, Ciobanu, Blaga, & Budulan, 2010).

Overview of Knit Garment Production

As textile technology and processes have evolved throughout history, manufacturing ease and speed have been at the forefront of innovation. Knit garments are created using three different processes: cut and sew, fully-fashioned, and WholeGarment® knitting. (Choi & Powell, 2005). The word "seamless" is used to describe an array of different production processes that range from a method that eliminates one or more seams to a garment with no seams or sewing required. For the purpose of this study, a seamless or WholeGarment® was defined as one that requires no sewing or linking once it comes off the machine as an entire garment.

Cut and sew. Cut and sew construction is a common and wasteful garment production method being used today. Beginning with one complete piece of fabric, the individual garment pattern pieces are cut out of the fabric, as shown in Figure 6. The fabric that is left behind is often thrown away. It has been estimated that the average garment waste generated is around 15% of the total mass (Rissanen, 2005). This assembly method is labor intensive as each garment or product has to be cut out and sewn before it reaches the consumer (Choi & Powell, 2005). Despite the waste created, this production method can be preferable because it is the most popular form of knit garment production. It also allows fabric defects to be easily excluded from the final pattern pieces by cutting around the damaged areas. Because this is the main method of production, many designers and production teams know, easily use, and understand this technology better than new knit advancements like fully-fashioned and WholeGarment®.

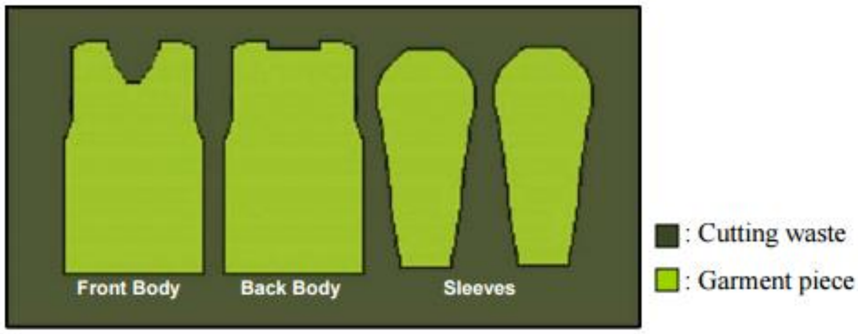


Figure 6. Cut and sew production method (Choi & Powell, 2005, p. 9).

Fully-fashioned knitted garments. In an effort to decrease waste and reduce labor, fully-fashioned knitwear was introduced in 1995. *Fully-fashioned* means an object is "shaped wholly or in part by widening or narrowing of piece of fabric by loop transference in order to increase or decrease the number of wales" (Denton & Daniels, 2002, p. 308). It is through this adding and subtracting of stitches to the piece that shaping and fashioning marks are formed. Fashioning lines or marks refer to the diagonal knit stitches on edge of a fully-fashioned garment, and they help shape the garment. These marks indicate where the knit stitches are being transferred to narrow or widen the fabric to the desired shape, as seen in Figures 7 and 8 (Choi & Powell, 2005).

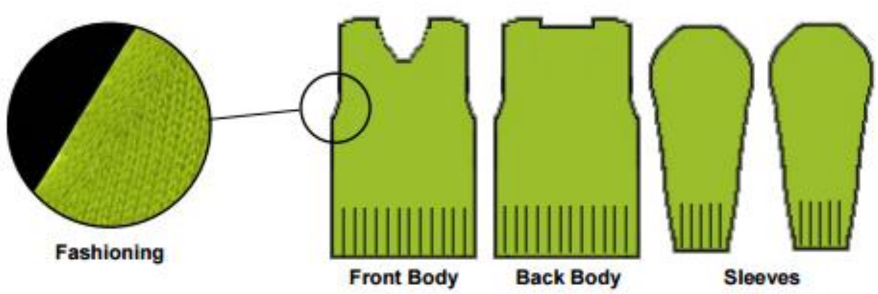


Figure 7. Fully-fashioned production method (Choi & Powell, 2005, p. 9).

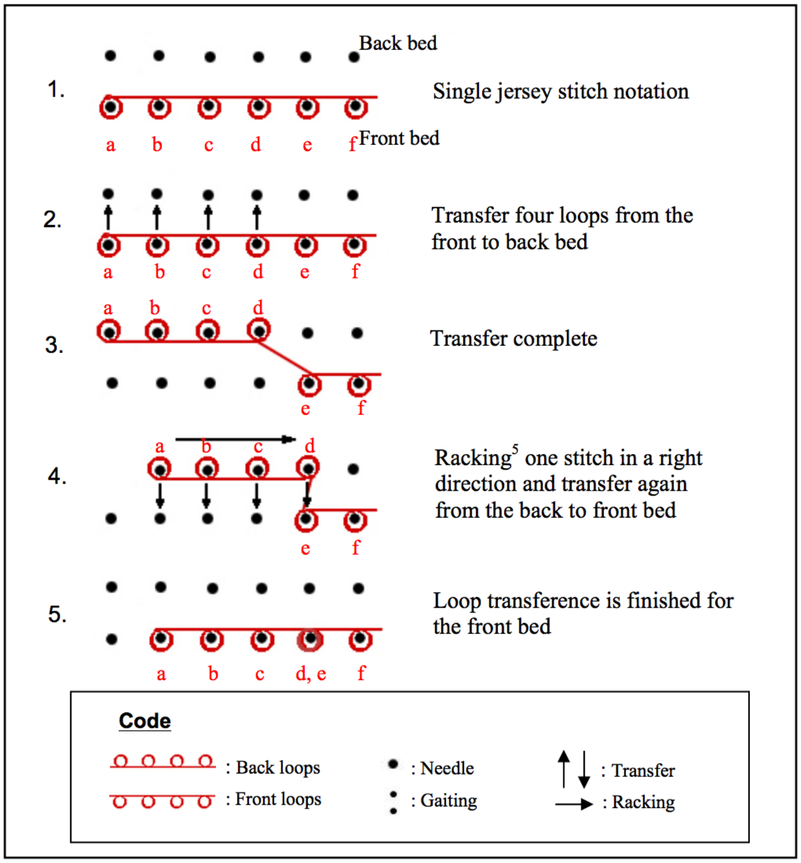


Figure 8. Knit notation for narrowing (Choi & Powell, 2005, p. 10).

While this method of production produces less waste and eliminates the need to cut individual pattern pieces, fully-fashioned knit pieces still need to be joined and assembled. This assembly is done with linking or cup seaming. *Linking* involves joining side seams and fabric edges by lining up and connecting individual stitches of the fabrics with a row of knitting. *Cup seaming* stitches the fabric edges together (Gartshore, 1983).

WholeGarment® knitting. While the first fully automated, seamless glove machine was introduced by Shima Seiki in the 1970s, it was not until 1995 at the International Textile Machinery Association (ITMA) Exhibition in Milan, Italy, that the first computerized WholeGarment® knitting machine debuted to the world (Shima Seiki, n.d.). WholeGarment® is made possible by the machine's ability to partial knit during a knit course. Partial knitting allows the machine to knit only a small section of a row of stitches, moving stitches outward or inward to shape the garment to the desired width. Throughout the next decade, those in the industry sought to simplify the programming and software in order to integrate this new technology into the marketplace (Evans-Mikellis, 2011). Seamless or WholeGarment® technology produces a complete garment that requires no joining or sewing methods, cuts down dramatically on labor costs, increases productivity, and offers manufacturers a chance to react quickly to trends, and it also is a virtually wasteless process (Choi & Powell, 2005; See Figure 9).

Figure 9. WholeGarment® knitting production method (Choi & Powell, 2005, p. 11).

Starting with the SWG-series in 1995, Shima Seiki has been developing ranges of knitting machines for manufacturing knit products (Shima Seiki, n.d.). By replacing the traditional latch needle with their SlideNeedle design, they were able to create a more efficient and effective machine that transfers stitches with ease. Instead of opening through a latch design like a traditional needle, its hook slides down into the shaft of the needle. This new needle design marks one of the only changes to the traditional latch needle since its implementation 150 years ago (Gabel, 2015). While other companies such as Stoll are also researching and developing complete garment and seamless knitting machines, Shima Seiki was the main focus of the current study, as they manufacture the machines used for this research.

User Comfort

Considered a human necessity by many but decidedly hard to define, comfort has been a nebulous term, especially when it comes to clothing. Slater (1977) said that comfort "is a personal sensation that can be determined by the physiological, neurophysiological, physical, and psychological states of a human in a given environment" (p. 1). Others have broken down the notion of comfort into various categories, such as emotional, physical, mental, and environmental comfort (Brogna & Fellow, 1976).

Physical comfort. As the focus of the current study was on the physical comfort of a garment, three major aspects of clothing comfort were addressed. They can be seen in Table 2.

Table 2.
Major Aspects of Clothing Comfort (Song, 2011, p. 22)

Aspect of Comfort	Definition
Thermal Comfort	Attainment of a comfortable thermal and wetness state; it involves the transport of heat and moisture through fabric
Sensorial Comfort	The elicitation of various sensations when a textile comes into contact with skin
Body Movement Comfort	Ability of a textile to allow freedom of movement, reduce burden, and body shaping, as required

Sensory comfort and measurement. Usually described as the *hand* of a fabric, sensory comfort mainly involves stiffness, softness, and smoothness to help consumers and researchers describe how a fabric feels to the touch. Wide variations can occur within sensory testing, as each person will describe and interpret a given fabric a little differently. However, in order to make these sensory observations more objective, laboratory tests have been established to measure stiffness and other aspects of sensory comfort (Song, 2011). Stiffness testing is of prime importance in this comfort category.

Within sensory comfort, fabric hand has been a key factor and is considered perhaps the most important subjective quality of a garment to consumers. Peirce (1930) was the first to conclude the following:

> “The quality of the finish of a cotton fabric is a matter that concerns its appeal to the judgment of the buyer on the evidence of his senses . . . It would be futile to pretend to replace expert of aesthetic appreciation by the numerical result of a physical test. The evidence of the senses, on the other hand, depends on the physical properties of the

> material, so that physical measurements can be of great value in providing data upon which to exercise judgment." (p. 378)

Based on these findings related to measuring fabric hand, the Kawabata system (KES-F) was created in 1972 to measure what Peirce determined to be the most influential aspect of the hand—stiffness (Kawabata & Niwa, 1989). Kawabata and Niwa (1989) created this system by studying how fabric experts touched and manipulated fabric to test the fabric hand. They referred to the way fabric experts move and bend the fabric as "fabric deformation." These fabric deformation movements were then mechanized into instruments. KES-F consists of five basic measurements for hand: shear, tensile, bending rigidity, compression, and surface roughness. These measurements of hand are quantified by four instruments that make up the KES-F system. Using these various tests, an overall rating of the hand can be reached using a scale of one to five, with five being the best rating (Kawabata & Niwa, 1989). This system is "based on the general agreement that the stimuli leading to the psychological response to the fabric handle are entirely determined by the physical and mechanical properties of fabrics" (El Mogahzy, Kilinc, & Hassan, 2011, p. 48).

METHODOLOGY

This research was designed to explore the use of flatbed knit spacer fabrics in performance apparel. The goal was to determine whether this type of spacer fabric improved the comfort of rock climbers while climbing. After producing two flatbed knit spacer fabrics, testing to determine fabric weight, thickness, and strength was conducted at NC State University to understand the use of this fabric in apparel applications. Compression and surface roughness testing were used to compare these elements of fabric hand between the two spacer fabrics and a purchased, control base layer fabric.

Once the fabric-level testing was complete, the control base layer and two spacer fabrics were sewn into three separate base layer pants for garment-level testing. All three fabrics were sewn into regions of a base layer garment that come into contact with a rock climbing harness. These padded regions correspond to the areas of the body that are put under the most pressure while climbing. Wear trials were then completed with experienced rock climber volunteers at NC State University Recreation's rock wall. Participants completed surveys to compare the various aspects of fabric hand and sensory comfort while walking and climbing as well as provided their overall impressions of the three pairs of pants.

Research Questions

This research was guided by the following questions:

1. What are the differences and similarities in fabric hand between the spacer fabrics created and base layer fabrics?
2. When used by rock climbers, do these spacer knit fabrics increase user comfort without affecting garment performance?
3. Which of the three pants tested do participants believe performed better for rock climbing applications, and why?

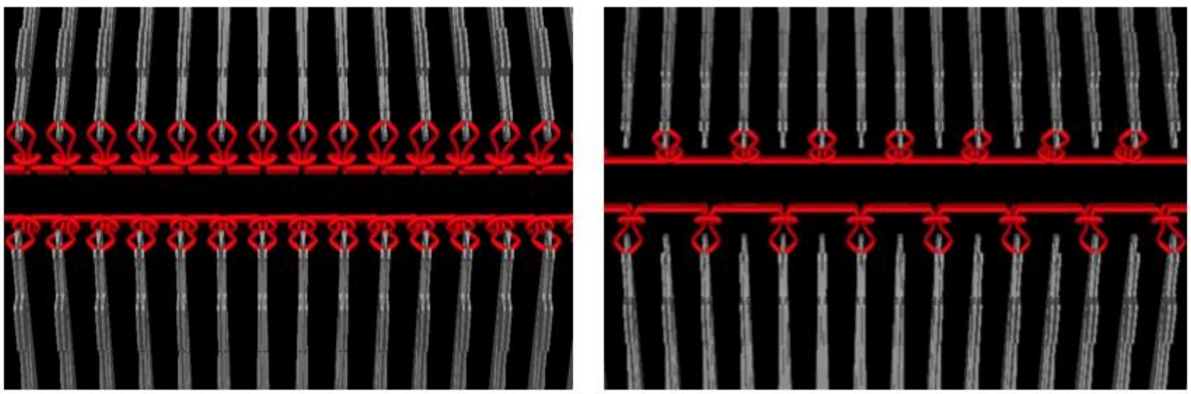
Technology and Machinery

To develop the flatbed knit spacer fabrics, the first step was to identify machines capable of creating this fabric structure at NC State University's College of Textiles' Knitting Laboratory. The following machines were capable of producing flatbed spacer fabrics: SWG061N$_2$, SWG021N, and SRY123LP. All of the machines have two needle beds. The SWG061N$_2$ and SWG021N machines are both part of the SWG-N series and have independently moving carriers and one carriage while the SRY123LP has one large carriage that moves the carriers (Shima Seiki, n.d.). The SWG-N machines, shown in Figure 10, were chosen over the SRY123LP machine for their superior development of spacer knit programming in Shima Seiki's SDS-ONE Apex 3 software.

Figure 10. Shima Seiki SWG-N_2 series machine (Shima Seiki, n.d.).

These machines also have a multitude of independently controlled yarn carriers and better machine and stitch reparability while sampling in comparison to the SRY. Though originally designed as small WholeGarment® machines for gloves, hats, and other accessories, the SWG-N series machines have proven to be capable of producing apparel and industrial and medical knit items, such as footwear and medical meshes. All samples for this study were produced on the SWG061N_2 instead of the SWG021N because of the machine's width of 60 cm (24 inches) compared to 20 cm (10 inches), respectively. The SWG061N_2 machine is a 15-gauge machine. Neither machine was capable of producing adult-sized seamless knit garments for this study, which led to the use of cut and sew garment production.

The SWG-N series machines have the ability to knit in half gauge, meaning an item can be knitted on all 15 needles per inch or can be programmed to use only 7.5 needles per inch (i.e., every other needle). This makes the fabric less dense as the gauge changes from 15 to 7.5 with the same size yarn but half the number of knit stitches per inch. Because the stitch must go over two needle widths, half gauge knitting has fewer loops per inch. This reduction in loops leads to less coverage and lower density than a full gauge knit fabric made with the same yarn. This difference in stitches per inch can be seen in Figure 11, which depicts the change from full gauge to half gauge on a flatbed machine.



Full Gauge Flatbed Knit Half Gauge Flatbed Knit

Figure 11. Comparison of full and half gauge knitting on the needle bed of Shima Seiki's $SWG061N_2$.

The ability to knit in half gauge is what allows the machine to produce a tube with spacer fabric and other more complex knit structures. The machine uses the empty needles on the needle beds to transfer knit stitches between the front and back beds. The way the machine uses the empty needles for spacer fabric production will be discussed in the following section.

Knitting Technique

The $SWG061N_2$ has the ability to knit a spacer fabric structure into a tube, which can be programmed into a seamless garment or item. As discussed above, this is possible because the machine can knit in half gauge. Half of the needles are used to knit the spacer fabric structure while the other half are used to knit the jersey fabric for the back, creating a tubular item as shown in Figures 12 and 13. Figure 12 shows a diagram of the machine layout of a tubular item with spacer fabric structures knit into the front. When knitting this spacer fabric into a tube, four yarn carriers overall are used, three for the spacer fabric layers and one for the tube.

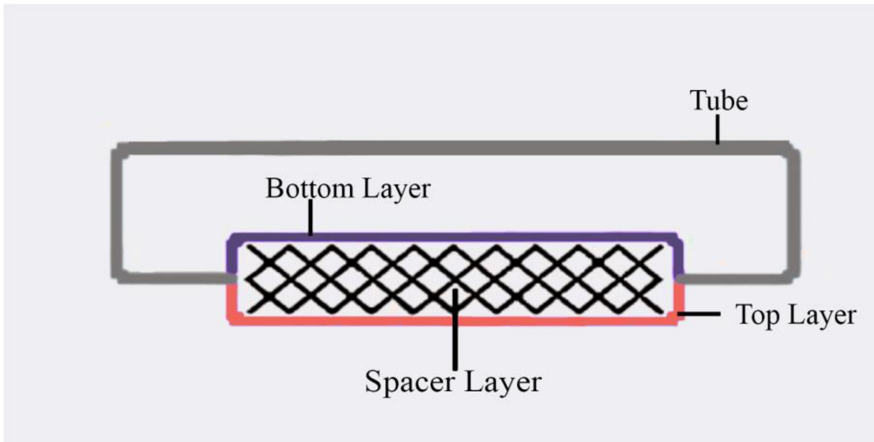


Figure 12. Diagram of how flatbed machines can knit spacer fabric into a seamless tubular item.

The first yarn carrier (gray) knits the tubular item. The second yarn carrier (pink) creates the front layer of the spacer fabric and the third yarn carrier (purple) knits the back layer of the spacer. The final, fourth yarn carrier (black), knits the spacer layer. This spacer layer is tucked behind the top layer loop so it is not visible when looking at the technical face of the fabric. In order to easily see the different layers of the spacer fabric in a knit tube, four different colors of yarn were used to make the spacer fabric samples, as shown in Figure 13. The steps the machine takes to knit a row of spacer fabric in a tube are shown in Figure 14.

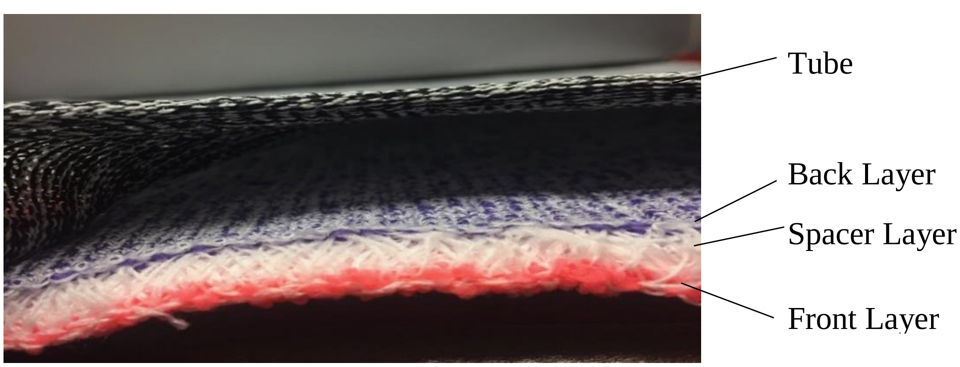


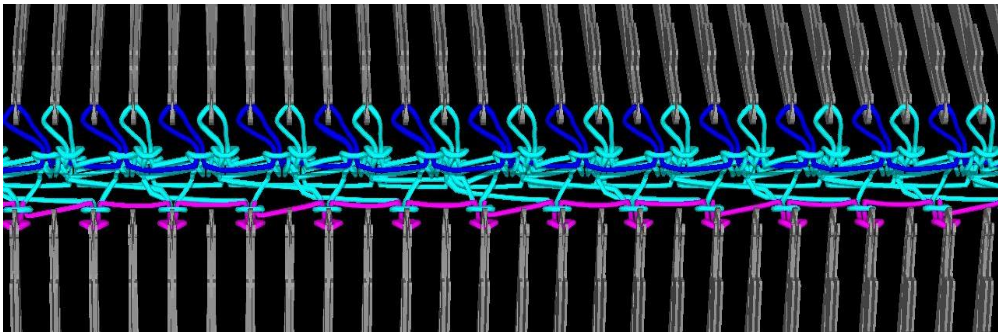
Figure 13. Spacer fabric knit into the front of a tube.

Figure 14. Steps to knit one row of spacer fabric in a seamless knit tube.

Tube Bottom Layer Top Layer Spacer Layer

Step 1: The top layer is on every other needle on the front bed. On the back bed, the tube and bottom layer are on alternate needles.

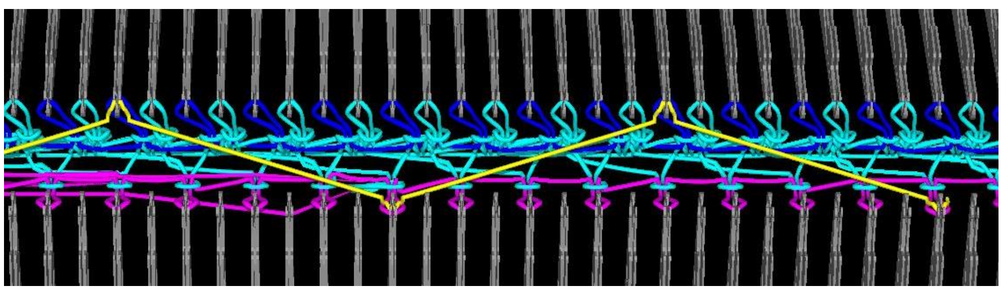
Back Bed



Front Bed

Step 2: The spacer layer has completed its first line of tuck stitches between the top and bottom layers. This spacer fabric is designed to have one tuck every eight needles.

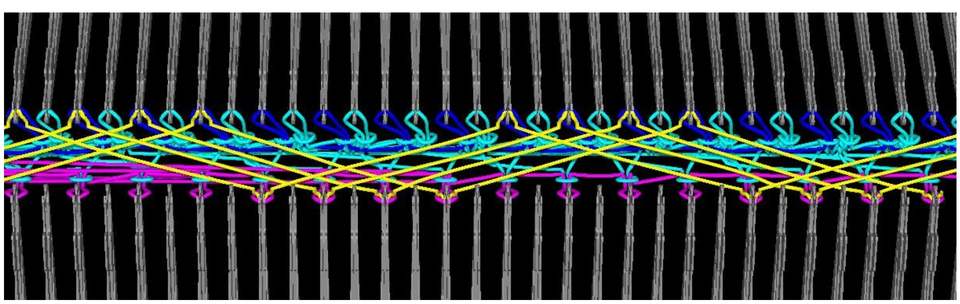
Back Bed



Front Bed

Step 3: The spacer layer for this row is half complete.

Back Bed

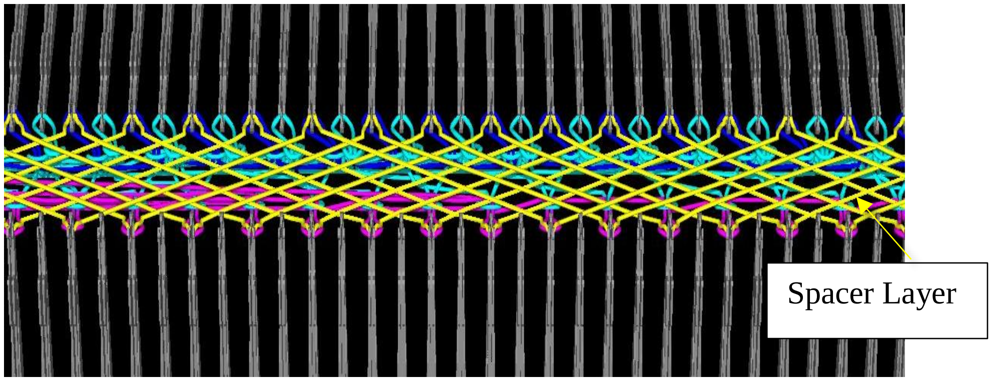


Front Bed

Step 4: The spacer layer is now complete.

Back Bed

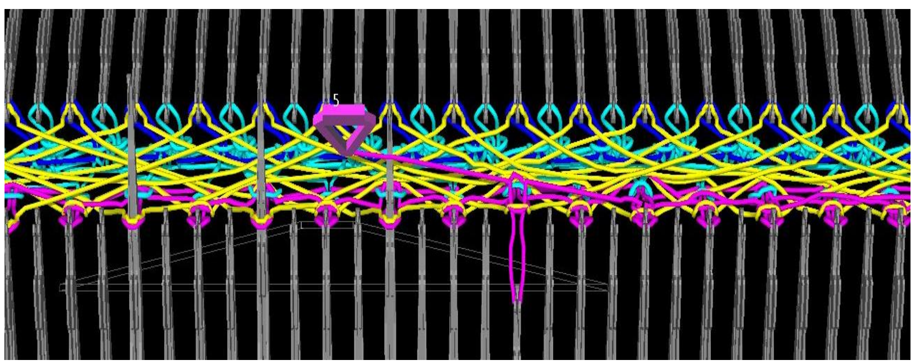
Front Bed



Step 5: A new row of top layer is knit on the front bed. In this step, the needles rise to knit the new stitch before lowering to cast off the previous stitch.

Back Bed

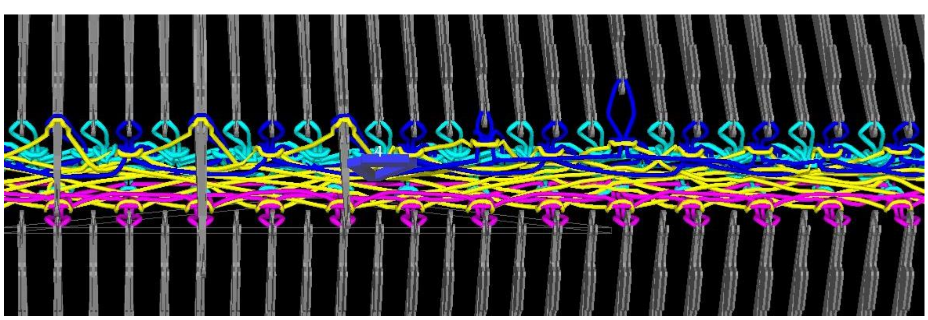
Front Bed



Step 6: A new row of bottom layer is knit on the back bed. Again in this step, the bottom layer needles rise to knit the new stitch before lowering to cast off the previous stitch.

Back Bed

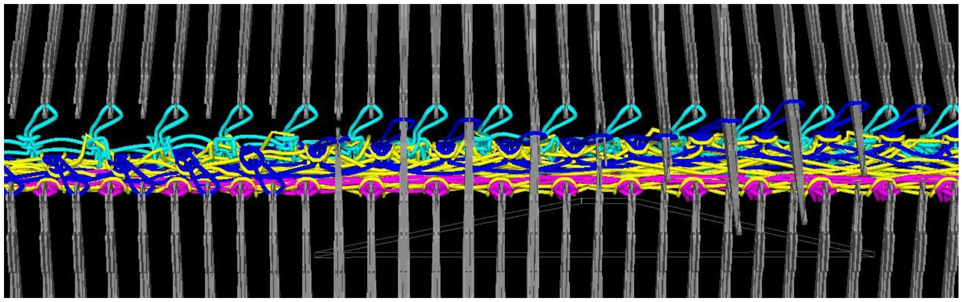
Front Bed



Step 7: Each bottom layer stitch is transferred from the back to empty needles of the front bed.

Back Bed

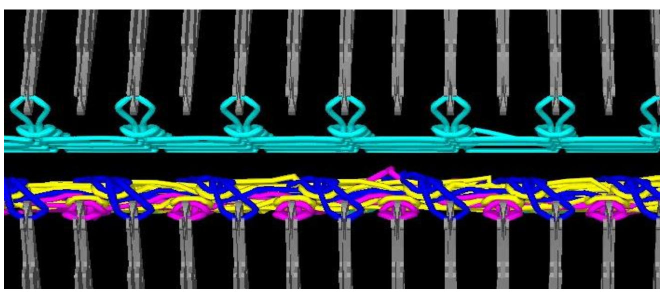
Front Bed

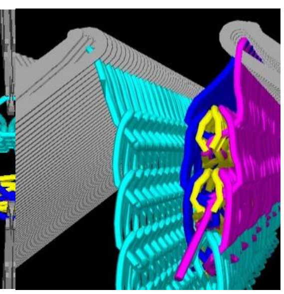


Step 8: The spacer fabric is now on every needle of front row. A new row of tube is knit on the back bed.

Back Bed

Front Bed



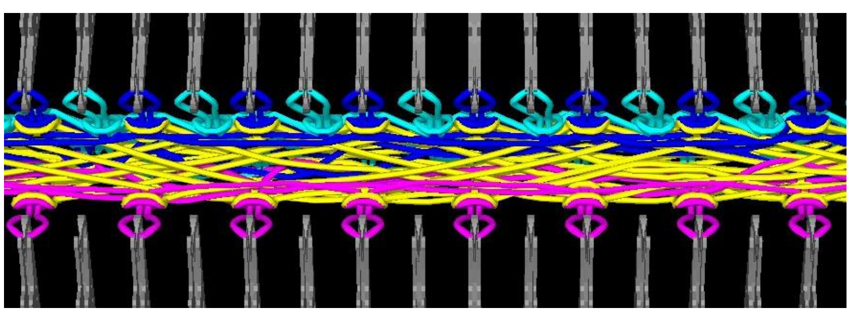


Side View

Step 9: The bottom layer is transferred to the back bed. A row of spacer layer is ready to be knit.

Back Bed

Front Bed



Once this process of knitting was understood, it was determined that three different fabrics would be tested in this study. The first was a purchased base layer fabric. The second was a combination of the knit structures used in the base layer and spacer fabric. The third fabric was a complete spacer fabric. These fabric structures and the resulting fabrics are shown in Figures 15 and 16.

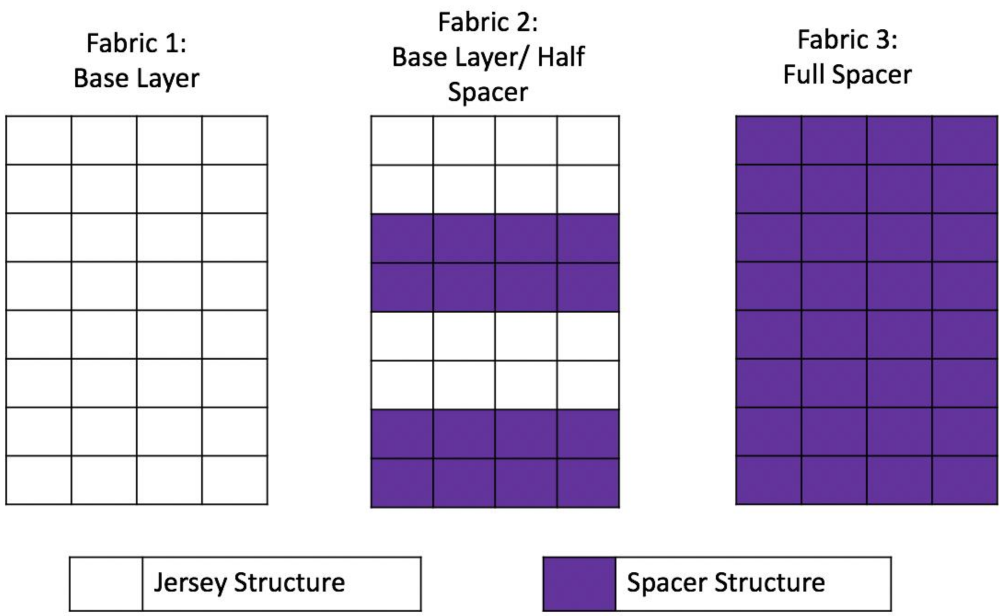
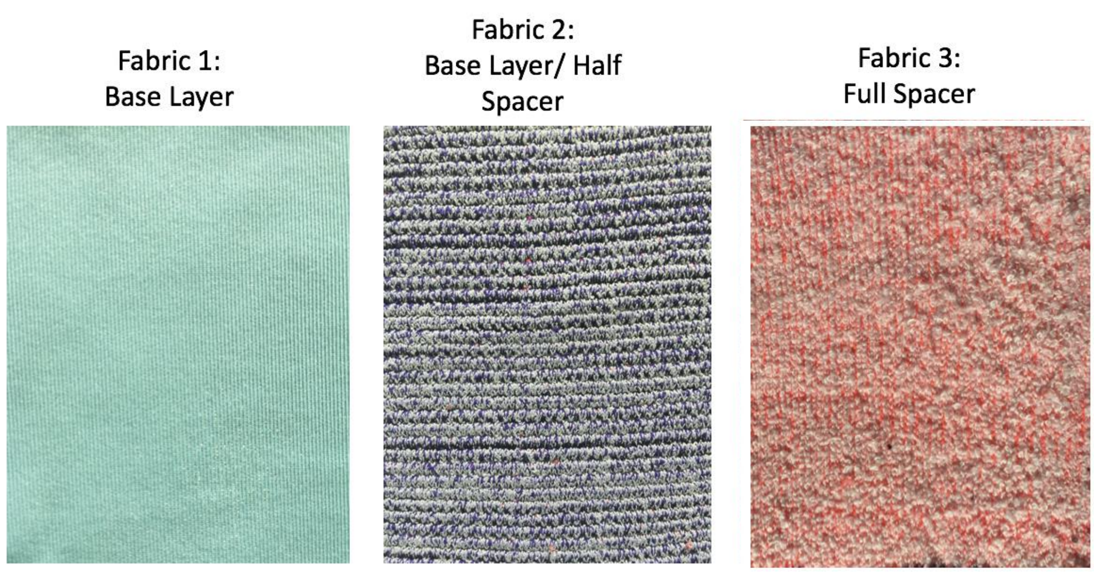


Figure 15. Knit structures of test fabrics.



Fabric Purchased Fabric Created for Study Fabric Created for Study

Figure 16. Test fabrics-technical front.

Machine Capabilities

Independently controlled carriers and the take down of the fabric of the SWG-N series enable the machines to add and subtract different colors and yarns into a knitted item. These color changes are possible because an arm-like gripper on the machine can move to the yarn's location, disconnect it, and move it to any position on the machine. This allows the machine to add and subtract yarn carriers and colors when necessary. This adding and subtracting of yarns at any point in the design would be more difficult and take longer with the SRY series because each carrier must be moved by one large carriage across the entire width of the fabric. This carriage must move across the entire width of the fabric and knits entire rows at a time, where the SWG-N series can be programmed to knit different parts of a product with only certain carriers. Therefore, the gripper is a faster option for adding and subtracting yarns.

Complete with Shima Seiki's SlideNeedle™, 10 yarn carriers, special yarn grippers for yarn color changes, and holding hooks for yarn cutting and holding, this machine is equipped to produce multi-color knit designs and accessories. The spring-type sinker system on the machine also allows for control over stitch movement and tension. During knitted fabric production, the stitches need a force, either pushing from the top or pulling from the bottom, to weigh the knit stitches down. This force allows old stitches to easily slide off the needles to make room for the next course of knit stitches. These sinkers in the holddown position push the stitches downward in order to create more uniform knit loops, as shown in Figure 17. This position supplies the force needed for the old stitches to come off the needles. The springer-type sinkers on the SWG061N_2 allows for more complicated three-dimensional patterns to be knitted while still retaining high quality (Shima Seiki, n.d.).

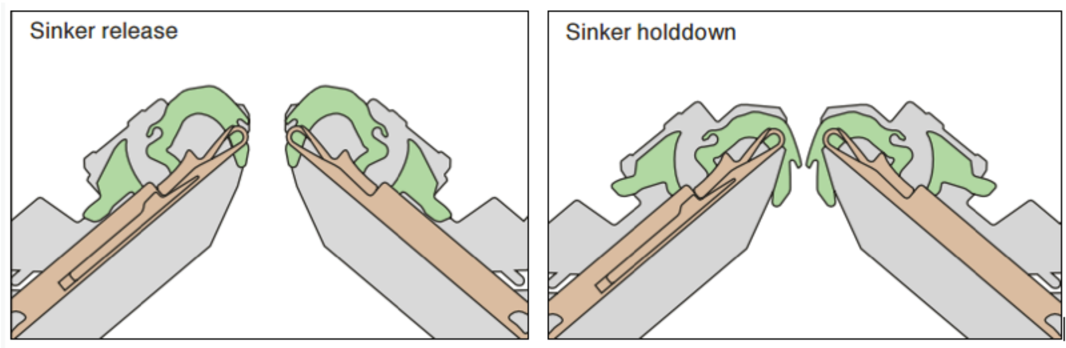


Figure 17. Illustration of sinker position and holddown capabilities on flatbed machine (Shima Seiki, n.d.).

Knit Machine Software

The exploration of how to incorporate spacer fabrics into clothing began with the SDS-One Apex3 software systems. Shima Seiki machines require specific software for programming knit designs. This software is available exclusively on their SDS-One Apex3 system. Knit programming was completed in KnitPaint™, a portion of the software system that is specific to knit structure programming. Programming a spacer fabric for the $SWG061N_2$ WholeGarment™ machine started with creating the base object into which to knit the spacer structure. Figure 19 shows the initial steps of creating a tubular item in the software and then the programming of basic dimensions and settings of the knitted item.

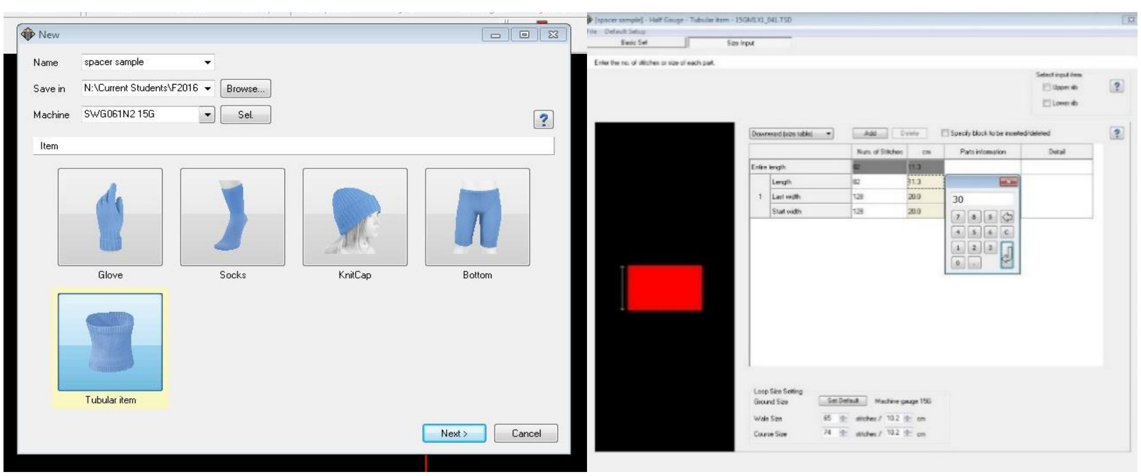


Figure 18. KnitPaint™ item selection and dimension input windows.

When programming for the $SWG061N_2$ WholeGarment™ machine, users can automatically add spacer fabric to a certain area of a tubular object in the KnitPaint™ software. Flatbed spacer fabric thickness was determined by the distance between the needles the spacer layer yarn was tucked behind. In the KnitPaint™ software, users can program the thickness of the spacer knit fabric by assigning the number of needles between tucks, which is referred to as the "tuck pitch" in Figure 19. All spacer knit fabrics created in this study were one tuck per every eight needles. Keeping a constant tuck pitch ensured that the tuck pitch count was not a variable in later thickness measurements.

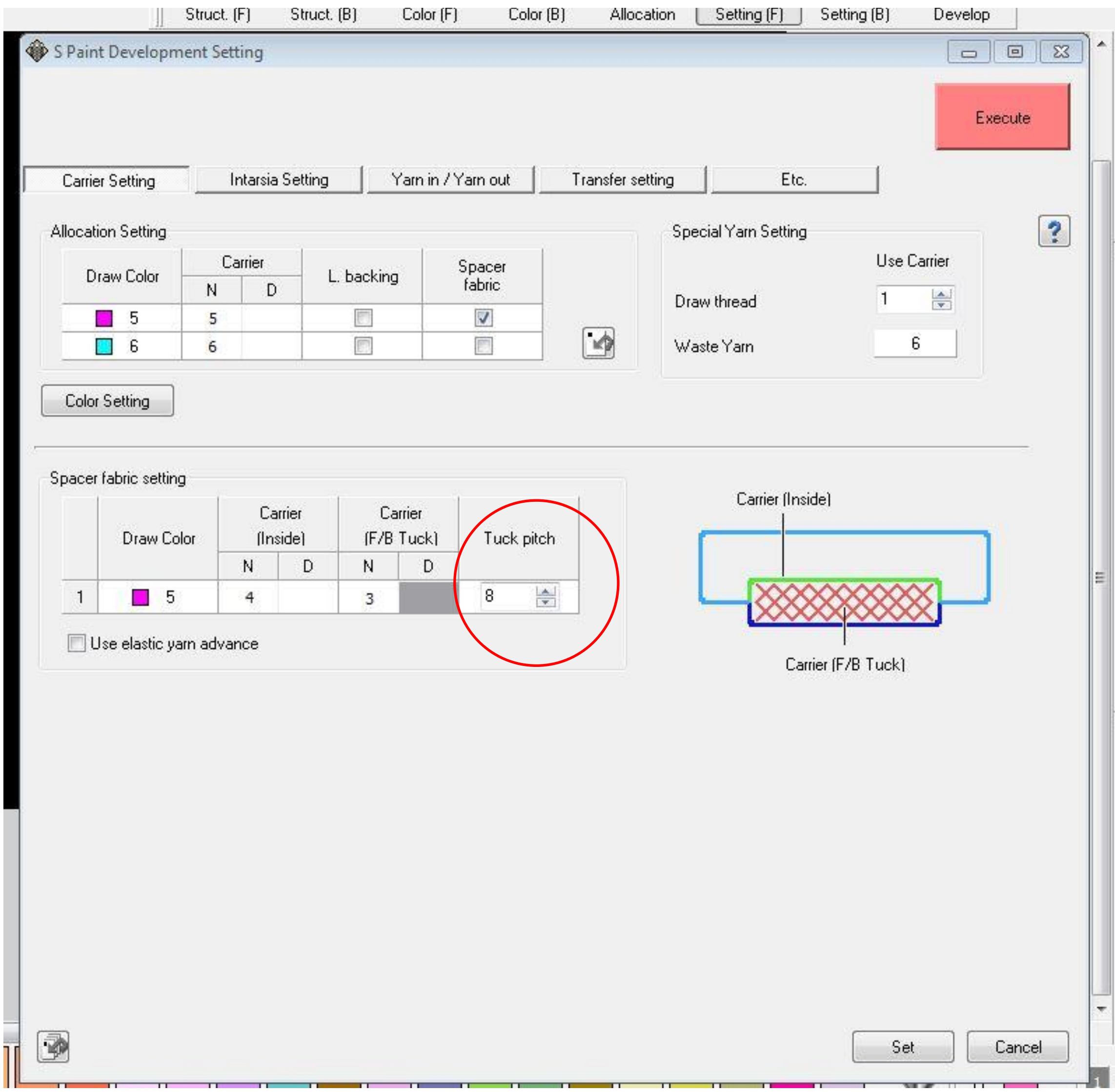


Figure 19. KnitPaint™ window that shows spacer fabric thickness programming.

Yarn and Machine Settings

Researchers agree that user comfort is of the greatest importance when it comes to designing and constructing clothing (Duru & Candan, 2013; Shishoo, 2005). When determining the best fiber and yarn to use for this study, athletic apparel trends, as well as studies on yarn properties for sportswear, were researched. While both synthetic and natural fibers are used in sportswear, polyester is the most common fiber in this market. When it comes to sports apparel, "liquid transporting and the drying rate of fabrics are . . . two vital factors affecting the physiological comfort of garments" (Duru & Candan, 2013, p. 591). Polyester has low moisture absorption, is relatively inexpensive to produce, and is easy to care for and launder, which makes it a popular fiber among sportswear companies. Polyester is also hydrophobic in nature, which means it does not readily absorb water as do other fibers, like cotton. Therefore, polyester helps keep athletes more comfortable with quick drying and moisture wicking clothing. These characteristics and other finishes that can be applied to polyester to enhance fabric performance make it the most common fiber in sportswear. Improved spinning and extrusion techniques for polyester make it possible for unique characteristics, such as waterproofing, moisture wicking, anti-microbial, and even fire retardant finishes, to be added to synthetic yarns (Shishoo, 2005).

With these studies in mind, polyester-based yarns were the main fiber used in this research. Initially, jersey samples were produced to test three different types of polyester yarn. The yarns used were a yarn produced by Sapona Manufacturing (the Sapona), a textured polyester and elastic plied yarn, and Unifi's All-in-One® (aio®) and Sorbtex® polyester yarns were knit in simple jersey samples. The aio® yarn was designed for performance applications and features five of Unifi's performance finishes and characteristics, including permanent odor control, UV protection, moisture management, soil release, comfort, and performance stretch. The aio® yarn is 185 denier recycled polyester with a 134 filament count. Sorbtex® yarn has the same moisture management properties and is 185 denier as well. However, it lacks the other performance finishes that aio® possesses. The Sapona is 20 denier elastic and 150 denier, 96 filaments, textured Cool-Wick polyester plied together. Plying means these two different fibers are twisted together to create a single yarn with both fibers. This yarn's content is 71% polyester and 29% spandex.

When comparing these three jersey samples to the base layer jersey, none of the sample fabrics had the same stretch or cover. The aio® and Sorbtex® fabric samples did not possess the same stretch and recovery as the control jersey knit. This could have been related to the fiber content, or the fiber make-up of the yarns used in the industrial sample, which was 89% polyester and 11% elastic. The main difference between the two fabrics was that the industry sample had more stretch. The Sapona fabric had less coverage and more stretch than the control jersey fabric, and the Sapona yarn broke more often on the machine, causing runs in the fabric.

Research into athletic clothing and movement shows that skin over joints such as elbows and knees can stretch as much as 50% while bent, so clothing made for activities where a wide range of motion is necessary must have similar elastic qualities (Voyce, Dafniotis, & Towlson, 2005). After Du-Pont's invention of Lycra, a rubber-based fiber, in 1958, elastane fibers have been integrated into sportswear to improve the stretch and recovery of a garment in order to increase wearer comfort. Base layer garments, worn close to the body and next to the skin, often have a percentage of elastic in order to move easily with the body (Voyce et al., 2005). The predominance of elastic and stretch in athletic clothing and base layers led to the integration of a more elastic yarn called Sapona into the aio® and Sorbtex® fabrics.

New jersey fabric samples were created with the aio® and Sorbtex® yarns being plied with one end of Sapona yarn, which created a similar fabric hand to the base layer sample. In these two new sample, the two yarns were run through the same carrier on the machine. Then, these samples went through abrasion testing performed on the Martindale Abrasion Tester at NC State University's Physical Testing Laboratory (See Figure 20).

Figure 20. Martindale testing equipment used for abrasion testing.

On this testing equipment, the samples of aio® and Sorbtex® plied with Sapona fabrics were placed into fabric holders that rubbed the fabric face over a rough, wool woven fabric. This machine moved the test fabrics in a set pattern for 20,000 cycles to simulate typical fabric wear. This testing was completed according to the ASTM D4966 testing standards to determine the change in fabric based on the fabric face, pilling, and other defects. This testing standard called for the use of woven fabric as the abrasive material (abradant) and a 9kPa weight added to each fabric holder to ensure uniform fabric testing. As neither fabric wore through completely after this many cycles, the pilling and the amount of fibers accumulated on the abradant were used to determine which fabric was more abrasion resistant. As shown in Figure 21, aio® outperformed the Sorbtex® fabric with less pilling and fewer fibers left on the wool abradant and the aio yarn combination was selected to use in the sample production. The resulting fabric was 94.4% polyester and 5.6% elastic. This fabric had stretch, odor control, UV protection, and easy care, and consists of mostly recycled polyester. The recyclability of spacer fabrics in comparison to other padding methods, specifically foams, which cannot be recycled, is a major benefit of spacer fabrics. By creating a spacer fabric that is made mostly of recyclable material, this study involved the use of a more environmentally conscious end product.

Figure 21. Abrasion testing for Sorbtex® (dark gray) and aio® (white) fabrics.

The majority of prior research into knit spacer fabrics, both warp and weft, used monofilament yarn as the spacer layer (Liu, Hu, Zhao, & Long, 2012). Monofilament is a durable and stiff yarn that is often used to create loft and space between top and bottom layers. Studies have shown that between monofilament and multifilament yarns in spacer fabric, monofilament yarns have a higher resistance during compression testing (Arumugam, Mishra, Militky, & Salacova, 2016). However, most of these fabrics are much thinner and more suitable for industrial seating or cushioning functions instead of apparel. When experimenting to use a 14 denier, monofilament for the spacer layer yarn on the SWG061N_2 machine, it did not knit on the machine as easily as the aio® and Sapona® yarns. Because the spacer layer is transferred between beds and monofilament has less stretch than the polyester and elastic yarn, the monofilament yarn tended to break much more easily, which led to many broken ends poking out of the top and bottom layers. The stiff nature of the monofilament spacer layer created loops on the sides of the spacer fabric when the carrier was changing direction to tuck the yarn between the beds. Through stitch length and yarn feeding experimentation, spacer fabric was created with monofilament yarn with significantly reduced broken ends, but there were still loops at the side and several broken ends. This final monofilament sample was tested against the polyester and elastic samples to better understand the differences between monofilament and polyester/elastic spacer layers in fabric hand and compression.

Another measure to control the sample uniformity was the stitch length settings used on the machine. The stitch lengths used on the machine were determined by the ease of machine performance and the desired cover of the fabric produced. Because this fabric was to be used as a base layer that is often worn as pants while exercising, the stitch length needed to be as tight as the machine would allow to create cover for the wearer. Once the stitch lengths for the fabric were determined, the same setting was used for each sample to ensure the fabrics were uniform.

After the spacer fabrics were produced, steam was applied to each sample. Often referred to as a finishing process, steaming helped the yarns in these fabrics to shrink up to their final state and reduce the likelihood of shrinking. Fabric 3, the all spacer fabric, shrank by 30.6% in the width direction after the steaming process. Fabric 2, the half spacer fabric, shrank by 20% in width and length. This shrinking process also caused the spacer layer to become denser and more tightly knit than its pre-steamed sample. The same yarn was used in both of these fabrics, which makes the difference in fabric shrinkage interesting. This could be due to the different in knit structures in fabric 2 and fabric 3, but further investigation would be needed to determine specifically caused this difference.

Physical Testing

For all three fabrics—the two spacer fabrics created and the purchased base layer fabric—basic measurements of weight, thickness, and strength were taken. Aspects of fabric hand, which describes the way in which the fabric interacts with human contact, were also measured through compression and surface roughness and smoothness testing.

Fabric measurements and bursting strength. To test fabric strength, burst testing was performed on all three fabrics on the TruBurst^2 machine. This machine works to burst the fabric by clamping it down with a small plastic dome to a plate with a rubber diaphragm in the middle. The rubber diaphragm then inflates up to 30mm in the dome while increasing the pressure exerted on the clamped fabric sample being stretched by the diaphragm. At some point, the fabric sample bursts, and the machine records the final diaphragm height, pressure it took to burst the fabric in psi, and the seconds it took to burst. This test is repeated 10 times per fabric. Then, a final test without fabric is completed to determine how much pressure it took the machine to inflate the diaphragm for that fabric sample. The software attached to the machine then subtracts this number automatically from the final data and outputs a sheet of all 10 trials with the accurate psi, diaphragm height, and seconds to completion. While these different measurements give researchers a look into the stretch of a fabric based on the diaphragm height and the time it took to burst, the major outcome from this test is the pressure it takes to burst the fabric. If a sample is too strong or too stretchy, the fabric can exceed the machine's capabilities. The maximum machine pressure is 125 psi, which includes the pressure it takes to fill up the diaphragm.

In addition to bursting strength, fabric thickness was measured. Following the ASTM standard for fabric thickness measurements (ASTM D-1777-96), the fabric was measured on an AMES Thickness Tester with 8.6oz (0.6psi) of pressure applied to each fabric. Each sample was measured five times before calculating a mean for each fabric. For this study, this thickness testing was performed three separate times. The first was on the three fabrics independently. The second round of testing was on the three fabrics when sewn with the pant fabric before wear trials, and the third round was after wear trials. The second and third rounds of thickness measuring were done to measure the difference in fabric thickness before and after the wear trial study. In the third round of testing, pant 2 in a size medium was unable to be measured. The AMES Thickness Tester that was used on the other samples was not measuring the fabric properly, and the data were not able to be retrieved. However, there were 20 measurements of pant 2 in other sizes, which provided adequate data for the pre- and post-use comparison.

Fabric weight was measured by punch weight and a king yield scale set up to only measure fabric weights. All measurements were performed after the fabrics were steamed and unused with the exception of the post-wear trial pant measurements.

Fabric hand testing. Usually described as the hand of a fabric, sensory comfort mainly involves stiffness, softness, and smoothness to help consumers and researchers describe how a fabric feels to the touch. Because fabric hand ultimately represents the way in which people respond to the touch and feeling of fabric against their bodies, mechanical testing is difficult because it tries to put numerical values to human sensory responses. Wide variation can occur within sensory testing, as each person will describe and interpret a given fabric a little differently. However, in order to make these sensory observations more objective, laboratory tests have been established to measure other aspects of fabric hand (Song, 2011). As the prototype fabric is created as an alternative to warp knit spacer and other 3D, foam-like fabrics, stiffness testing is of prime importance in this comfort category. As past researchers have noted, spacer knit fabrics are more breathable, have higher air permeability, and lower heat resistance than polyurethane foams (Gokarneshan, 2015; Liu et al., 2012). Because of this prior knowledge base and research, testing against polyurethane foams was not done during the current study. Instead, the focus of this study was on user comfort in garment applications as opposed to previous studies that tested seating upholstery (Hu, 2008). Stiffness in this garment is the largest contributor to ease of movement for the wearer of the garment with integrated seamless spacer fabric.

Fabric hand was evaluated using the KES-F system, which measures compression, tensile/shear, surface roughness, and bending/rigidity. Compression is measured by two circular plates having areas of 2 cm^2. These plates compress the fabric before measuring how long and to what extent the fabrics return to their original thickness. During compression testing, the linearity of compression/thickness curve, compressional energy, and compressional resilience are measured. Surface testing consists of an apparatus with piano wires that simulate fingers and measure the reaction between these wires and the fabrics. For surface testing, the coefficient of friction, mean deviation of MIU, and geometrical roughness are measured (Kawabata & Niwa, 1989). Fabrics 2 and 3 would not physically fit through the bending and rigidity testing, so physical lab testing of these characteristics could not be conducted. Human wear trials were conducted to better understand flatbed spacer knit fabric bending and rigidity compared to the jersey knit, commercial fabric used in climbing apparel today.

The Product and Design

The first step in integrating the spacer fabric into rock climbing apparel was to identify the areas on the body that are most affected by standard rock climbing equipment and may need additional padding to improve user comfort. Designed to be worn against the torso and placed above the hipbones with the leg loops high on the upper thigh, rock climbing harnesses are intended to be worn tight so the user has no chance of slipping out of the harness in any body position, as shown in Figure 22.

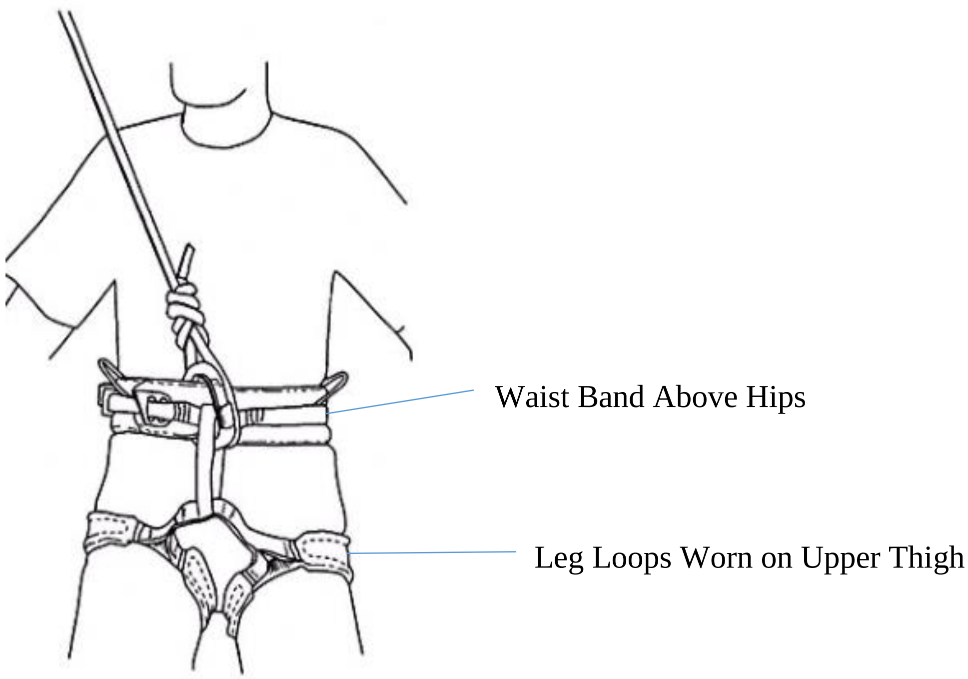


Figure 22. Frontal view of proper harness fit (Graydon, Hanson, & Mountaineers Society, 1997, p. 124).

The position in which climbers experience the most pressure on their body and are subsequently most uncomfortable is when they are in a completely seated position, referred to as “hanging,” in a climbing harness. In this position, the total body and gear weight is on the harness, which causes pressure on certain areas of the body. In order to understand exactly where these pressure areas occur, photographs were taken of a climber hanging in a harness, as shown in Figure 23.

Back of Climber Hanging in Harness

Side View of Climber Hanging in Harness

Back View of Harness Pressure Areas of the Body

Figure 23. Areas of pressure on body identified while using rock climbing harness.

Through these observations, the areas of the body that are most affected while hanging in a harness were identified. These areas were referred to in this study as the harness pressure areas. Figure 24 shows how these areas of the body were translated to areas on a base layer garment under a rock climbing harness. Because the harness must be tight against the body, base layer garments were the focus of the current study. The tightness of these padded areas against the body will help the padding stay in these harness pressure areas and limit the displacement of this padding under the harness while climbing. As seen in climbing gym and outdoor settings, many climbers, namely women, tend to climb in leggings, tights, and other base layer garments. For men, these base layers can be worn under baggy shorts or pants that are often worn by climbers at the gym. By sewing this padding into pre-existing pants, the issues of sizing and the comparison between traditional ways of inserting padding into clothing versus seamless padding were not additional variables.

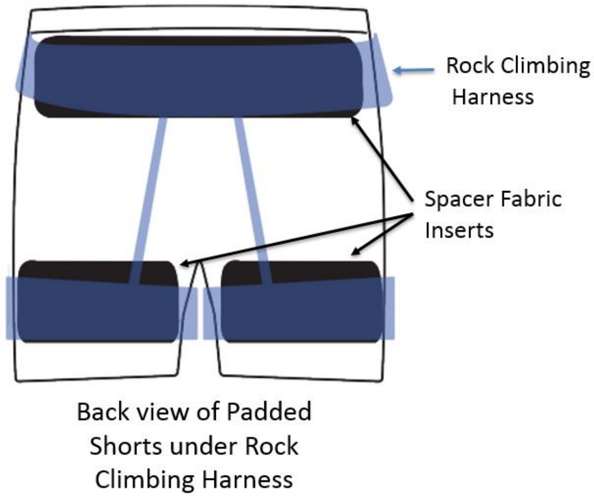


Figure 24. Position of padded areas of wear testing garments under rock climbing harness-back view.

Figure 25 not only shows where the spacer fabric was added to these garments, it also displays the padded for each of the three pants used in this wear testing. Pant 1 was the base layer, a jersey fabric with no spacer knit, pant 2 was an even ratio of spacer to jersey fabric, and pant 3 was completely spacer fabric in the harness pressure areas.

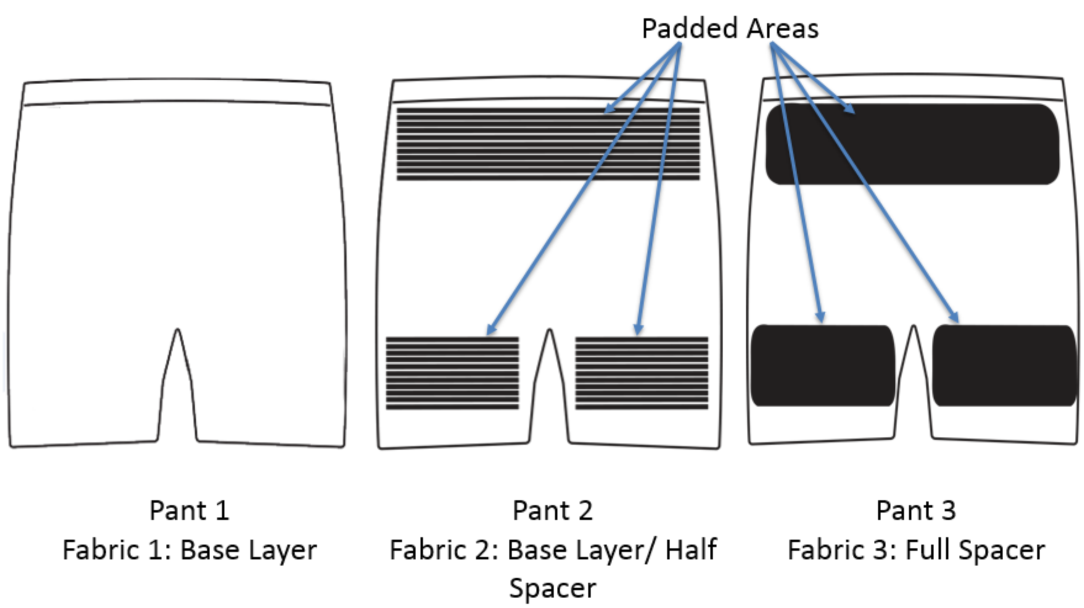


Figure 25. Garments for wear testing—back view.

It is important to note that all three pairs of pants were altered and extended 5 inches up the torso so the waistband and lower back padding would be under the harness pressure area of the back. The padding was then sewn into this extended tunnel area, and the elastic waistband on the pants was replaced at the top of this section and sewn back onto the bottom of the pants using a cover stitch machine. Further investigation, with the availability of a 90cm (36 inch) machine, would present the opportunity to create a completely seamless base layer shorts with spacer fabric knit into the garment.

Human Wear Trials in Comfort Testing

Though fabric hand physical testing, mentioned above, is integral in understanding elements of physical comfort on a fabric level, psychological comfort as well as garment level measurements are also measured through testing with humans. Because comfort is hard to define and can be represented by both qualitative and quantitative data, it is important to utilize both test methods when measuring comfort. Also, the spacer fabrics created for this study were too thick to be used on any of the bending and rigidity testing systems. Thus, these aspects of fabric hand were tested through human wear trials. For these reasons, wear trials were performed to understand user perceptions of fabric hand and spacer fabric integration into rock climbing base layer pants. Before performing any human wear trials or reaching out to potential participants, the Institutional Review Board for the Protection of Human Subjects in Research (IRB) at NC State University approved every aspect of the study, from consent forms to participant eligibility requirements and questionnaires.

When designing the wear trials portion of the study, usable and quality user feedback was the essential goal. In describing sensory testing and rating methodology, Hu (2008) mentioned that Likert scales are a common and simple way to measure aspects of comfort. This is because important elements of comfort are pre-determined, which helps participants assign a quantitative number to their sensations on a specific element of comfort, such as roughness or smoothness. This helps researchers pinpoint findings in a numerical and measurable way (Hu, 2008). This wear trial involved asking participants to assign a numerical value to pre-selected elements of comfort, including bending and rigidity. Researchers have found that having the positive quality on the right consistently throughout the study gives more uniform and accurate results. Instead of asking participants to come up with adjectives for the sensations they feel, specific areas of concern are addressed.

In order to understand whether participants felt the spacer fabric added comfort to their climbing experience, they were asked to sit in their harness for 2 minutes. As comfort has many different aspects and definitions, the focus in the current study was on the physical, weighted comfort of the climber in a harness and the range of motion of a climber's body when there is spacer fabric padding in base layer tights. This amount of time for participants to hang was chosen because it gave them a time range in which they felt the physical effects of sitting in a harness without feeling the physical pain and significant discomfort that can occur from sitting in a harness for longer, more extended periods of time. Bending and rigidity of the fabrics were the elements of comfort rated in these trials. After the three pairs of pants were tested, participants then filled out a final questionnaire about which pants they would most likely purchase, which pants they would be least likely to purchase, and why on both accounts. Participants rated their responses to prompts about whether they would wear pants with padding for rock climbing and whether they felt their comfort had increased based on having some padding in the pants they wore. This study did not involve an exploration of the moisture management or wicking capabilities that affect thermal comfort. In order to mitigate these factors affecting user responses, the trial was designed so participants would be encouraged to not physically overexert themselves during testing, and instead perform below their peak limits. At the end of the survey there was space for participants to give feedback on the overall concept, product, and ideas for future development and investigation.

All wear trial testing took place at the NC State University Recreation's rock climbing wall, shown in Figure 26. It was important during the trials to mitigate any macro-environmental changes to ensure more uniform results (Brogna & Fellow, 1976; Song, 2011). In this study, the same gym environment was used for each round of testing to reduce environmental changes.

Figure 26. Wear testing at NC State University Recreation's rock climbing wall.

Participants had to be over 18 years of age, have 6 or more months of rock climbing experience, be belay certified, and feel physically well enough to comfortably climb six routes in the gym in the time span of an hour. Because the activity of rock climbing has inherent hazards, only experienced rock climbers were used as participants to mitigate risk. All participants had already passed safety checks and were less likely to have an accident in comparison to newer rock climbers. This reduced the liability of the university and was designed to garner more accurate results from participants. Seasoned climbers were thought to be better participants than new climbers because they are emotionally, mentally, and physically accustomed to being 20 to 30 feet in the air in a rock climbing setting. After these participation parameters were established with IRB approval, potential groups and courses that would fit these requirements were identified. The Heath and Exercise Department of NC

State University has an outdoor leadership minor program that includes an Intermediate Rock climbing course that attracts students who fit within these criteria. On October 18, 2016, the principal investigator presented the basis of the research, the participation requirements, and what the study entailed to this group of students with the instructor's consent. On October 25 and November 1, 2016, the wear trials took place. In order to test more efficiently and keep within the IRB approved testing method, the course instructor shadowed the principal investigator through the entirety of testing one participant before becoming a secondary tester. All consent paperwork was handled by the principal investigator in paper form (See Appendix A). Surveys were designed and conducted through Qualtrics, survey software, for its data analysis capabilities and to reduce the use of paper. Participants filled out the paperwork on either a laptop or iPad that were provided in order to streamline the analysis process by starting with digital data.

Each participant tested three pairs of pants and was required to wear undergarments. All climbs were performed under the supervision of the Intermediate Course instructor, Scott Schneider. Photographs were taken during testing to document the process and environment with the permission of the participants. There were three different sizes of pants available, ranging from small to large.

First, participants were assigned a participation number to keep track of how many participants were testing as well as ensure anonymous results when discussing the answers in later data analysis. After filling out the consent forms, participants started testing with the first pant. They walked to the bathroom that was approximately 100 feet away from the rock wall to put on the pants. Once they returned from the bathroom, they put on the testing standard harness and answered four questions about their impression of the pants before climbing. These questions related to the stiffness of the pants while walking, temperature, bulkiness, stretch and how easy it was to put on the pair of pants and get all the padding in the proper location. Each question used a 5-point Likert scale arranged from negative to positive responses (See Figure 27). When describing the testing process and giving participant consent forms, any instruction on how the pants were to be worn was purposely withheld to see how participants would naturally wear the garments.

Please fill out the following questions concerning the different pairs of pants **BEFORE CLIMBING**. This section based on your first impressions of the pants while walking around in them and putting on climbing gear. If you need clarification on any terms or phrasing used, please ask for assistance.

Please rate the **stiffness** of the following pairs of pants while walking:

	Very Stiff	Somewhat Stiff	Neither Stiff nor Flexible	Somewhat Flexible	Very Flexible
Pant # 1	○	○	○	○	○
Pant # 2	○	○	○	○	○
Pant # 3	○	○	○	○	○

Figure 27. Likert scale and layout of Wear Trial Survey, Question 1.

Before starting to climb in each pant, each participant was asked to fill out questions about the following characteristics: stiffness while walking, the temperature of the pants, ease of putting the pants on, and the bulkiness of the pants under the harness. These characteristics were measured using Likert scales with different characteristics, as shown in Figure 27. These characteristics were later converted to numerical, ordinal data with values between 1 and 5. After the first four questions of the survey were completed, each participant climbed twice to the top of the rock wall before hanging in a seated position in a harness for 2 minutes. This hanging period was important because it allowed climbers to sit in their harness and test the pants while in the most uncomfortable position. Every participant had different climbing abilities and chose which route they took to climb the wall. They were encouraged to choose something they believed they could repeatedly climb with ease.

After this portion of the testing was over, participants answered five additional questions about the pants. These questions were related to their experiences while climbing and the following characteristics: stretch, extended seat comfort, temperature while exercising, smoothness, and stiffness while climbing. An overall rating Likert scale was the final question on this first page.

On the second page, participants were asked to indicate which pair of pants they would be most and least likely to purchase and why. Their opinions on whether they would wear pants with padding, whether the padding was noticeable, and whether the padding increased their overall comfort were also rated on a Likert scale on this page. Finally, they were asked what kind of pants they normally climbed in and to provide any additional feedback or thoughts in a text box provided.

During this wear trial, several controls were in place to ensure each pant was tested uniformly. The first control was that all the testing took place at the University Recreation's rock wall in an attempt to have the most stable macroclimate for testing possible. The second control was that each participant wore the same rock climbing harness. Because many of the participants owned their own rock climbing harnesses with various levels of padding and design features, each participant used Misty Mountain's Spectrum harness. This harness was simply constructed and adjustable to fit every possible participant, as shown in Figure 28.

Figure 28. Misty Mountain's Spectrum harness (Misty Mountain Threadworks, n.d.).

It was estimated that it would take between 30 to 60 minutes to complete each participant test, which influenced the number of participants taking part in the study. A sample size of eight to 12 was chosen because of the participation eligibility guidelines as well as the time it took to complete the full study. As participation in this study was completely voluntary, it was more difficult to find participants who were willing to dedicate the time to complete the testing because there was no incentive to participate. A total of 10 volunteers from the rock climbing course took part in the wear trials and ranged in age from 19 to 37 years old.

RESULTS AND ANALYSIS

Fabric Physical Testing Results

In order to compare the two spacer fabrics created for this study to the purchased base layer fabric, fabric-level physical testing was done to test strength, thickness, weight, surface, and compression. Table 3 shows the main data points collected from the physical fabric testing. Basic fabric measurements of weight, thickness, and fiber content were included in addition to the measures of fabric hand that were the main focus of the physical testing. These basic measurements were helpful in comparing the two spacer fabrics with the industry sample as a way of determining how different the two samples were from the fabric used in the industry. They were also helpful in understanding some of the physical changes that occurred simply by altering the knit structure between fully spacer and fully jersey. Fabric hand testing, compression, and surface testing were completed using machines, but stiffness and rigidity testing had to be completed through human wear trials because of the fabric thickness and machine limitations.

Table 3.
Physical Testing Results

Test Standard (if applicable)	Fabric 1: Base Layer (Purchased)	Fabric 2: Base Layer/ Half Spacer	Fabric 3: Complete Spacer
Fiber Composition	89% polyester, 11% elastane	94% Polyester, 6% Spandex	94% Polyester, 6% Spandex
Fabric Thickness ASTM D-1777-96	0.646 mm	2.744 mm	5.976 mm
Fabric Weight:	220 g/m^2	568 g/m^2	988 g/m^2
Bursting Strength ASTM: D3786/D3786M-13	99.15 psi/23.9mm	87.00 psi/29.0 mm	>125.6 psi of machine pressure[a]/ 23.1 mm
Compression Work Fabric Touch Tester	309.53 gf* mm	2109.15 gf*mm	4771.94 gf*mm
Compression Average Rigidity Fabric Touch Tester	1867.63 gf(cm^2*mm)	154.02 gf(cm^2*mm)	55.43 gf(cm^2*mm)
Surface Friction and Resistance Coefficient (MIU) KES-FB4 Surface Tester	0.4434	0.6532	0.7215
Fabric Surface Smoothness (SMD) KES-FB4 Surface Tester	4.2016 micron	10.7942 micron	11.2991 micron

[a]- Reading includes the pressure it takes to fill the diaphragm on the TruBurst[2] machine

Burst strength results. Following the ASTM D3786/D3786M-13 testing standards on the TruBurst^2 machine, the following data were collected on the burst strength of the three fabrics. Only fabrics 1 and 2 burst in the TruBurst^2 machine. Fabric 3 exceeded the maximum pressure the machine could produce, which was 125.62 psi. Figure 29 shows the burst strength tests of fabrics 1 and 2.

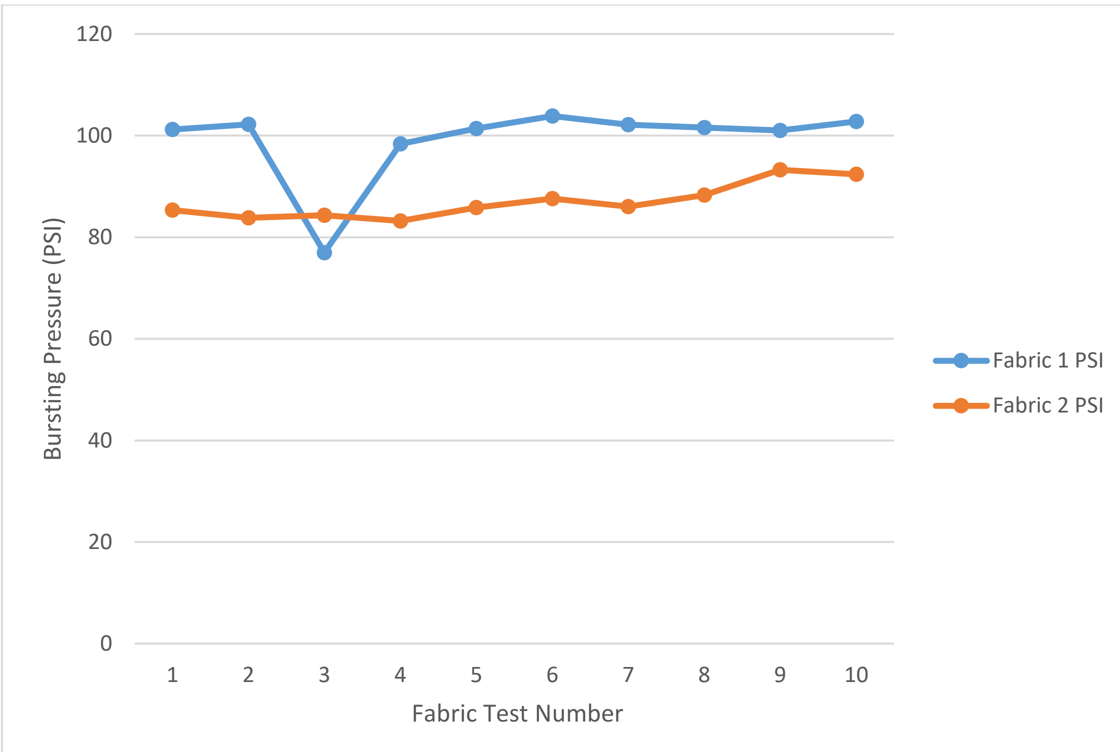


Figure 29. Burst strength test results for fabrics 1 and 2.

Tables 4 and 5 list the results for all 10 rounds of testing done for both fabrics, as well as the means, standard deviations, and percent of control variance for each measurement.

Table 4.
Bursting Strength Results for Fabric 1 (Base Layer)

Test	Burst Pressure (psi)	Diaphragm Height (mm)	Seconds
1	101.21	24.1	19.5
2	102.19	24.3	19.6
3	76.98	21.4	15.8
4	98.39	23.9	19.1
5	101.36	24.2	19.5
6	103.85	24.5	19.9
7	102.15	24	19.6
8	101.61	24	19.5
9	100.99	24.2	19.4
10	102.77	24.4	19.7
M	99.15	23.9	19.2
SD	7.92	0.91	1.2

Table 5.
Bursting Strength Results for Fabric 2 (Base Layer/ Half Spacer)

Test	Burst Pressure (psi)	Diaphragm Height (mm)	Seconds
1	85.34	30.2	19.5
2	83.82	27.9	19.2
3	84.29	29.3	19.3
4	83.2	30	19.2
5	85.84	30	19.6
6	87.62	28.8	19.9
7	85.99	28.3	19.6
8	88.27	28.5	20
9	93.26	29.5	20.9
10	92.39	27.4	20.7
M	87.00	29.0	19.79
SD	3.45	0.97	0.6

While fabric 2 had a standard deviation of 3.45 psi, fabric 1 had a higher standard deviation of 7.92 that was caused by one outlier test. As seen in Table 4 and Figure 29, the burst strength of fabric 1 on test 3 was 76.98 psi, which was 22.17 psi below the average burst pressure. Every other burst pressure was ± 3 psi from the average burst strength. In addition to the lower psi reading, the height of the diaphragm within the machine as well as the seconds it took the section of fabric to burst were both lower than the average. This round of testing caused the higher standard deviation in fabric 1 compared to fabric 2, and was mostly likely caused by a weak spot in the fabric sample. Because the machine functioned properly after this sample was taken and proceeded to display more uniform burst strength psi for the following fabric, it was most likely a fabric failure and not a machine failure.

Between fabrics 1 and 2, fabric 1 had a higher burst strength in psi but the diaphragm height of the sample when burst was greater in fabric 2, as shown in Tables 4 and 5. When performing the test, fabric 2 appeared to stretch more than fabric 1 against the ball-shaped diaphragm, as shown in Figure 30. The stretching of these individual stitches may have affected the burst strength of the fabric as two different knit structures were in this sample instead of one structure, as in fabrics 1 and 3. After fabric 2 had burst at a lower pressure than fabric 1, the plain jersey fabric that made up fabric 2 was tested to find evidence of whether it was the yarn that caused the drop in burst strength or the difference in knit structures. The plain jersey sample of the same yarn did not burst in the machine because the diaphragm exceeded the maximum height of 30mm. This means the fabric stretched to accommodate the full diaphragm height before enough pressure could be applied for it to burst. Fabric 2 had an average diaphragm height of 29mm, which was 5mm above the average of fabric 1. Also, repeated testing of fabric 3, made of the same yarns from fabric 2 and the jersey sample, did not result in any bursting, which may indicate the lower burst pressure of fabric 2 was a result of the different fabric structures and not the yarn strength.

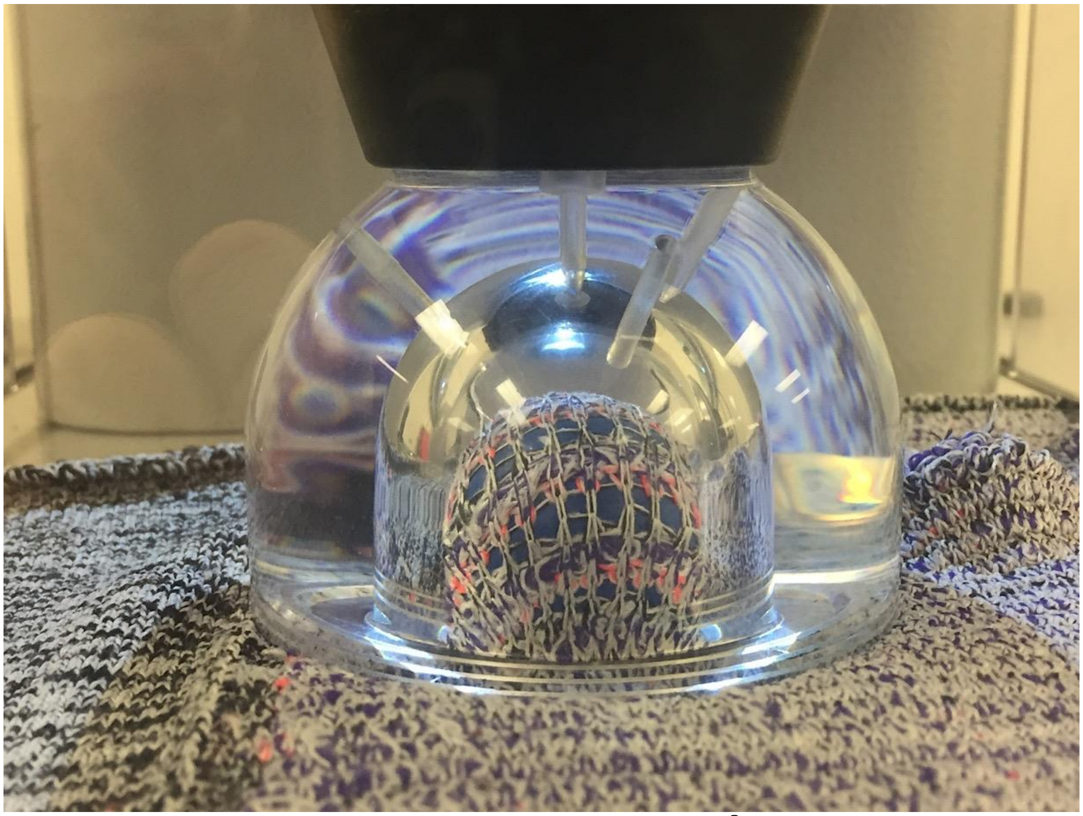


Figure 30. Fabric 2 stretched over the diaphragm of TruBurst^2 machine during testing.

Compression testing results. This test was performed on the Fabric Touch Tester Machine (FTT). The focus of this section is on the compression measurements and data from this testing, compression work, compression recovery rate, and compression average rigidity. As seen in Figure 31, the spacer fabrics took more force to compress than the jersey sample. This graph shows that fabric 3 was the hardest of the samples to compress.

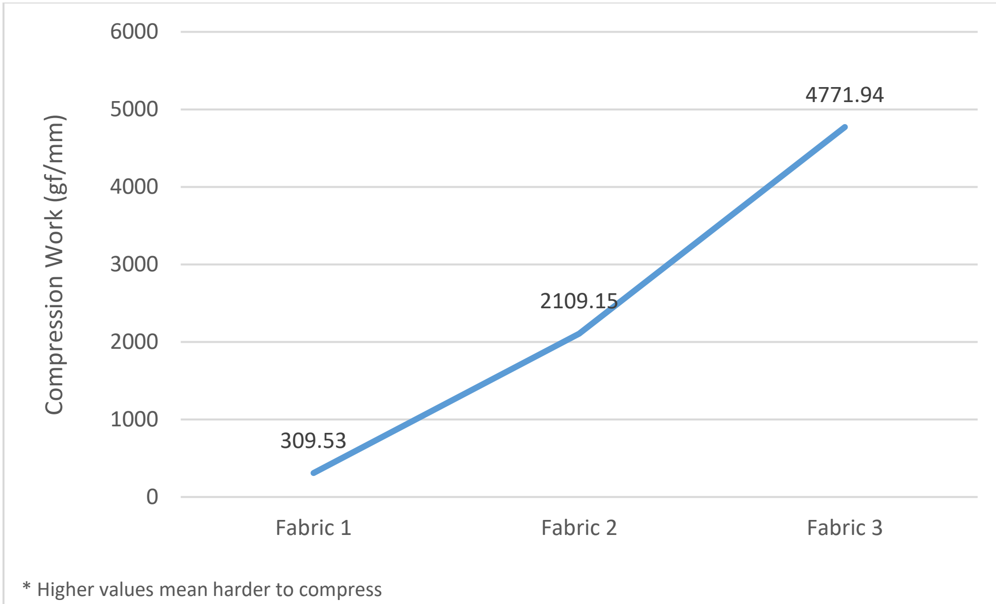


Figure 31. Compression work (gf/mm) of fabrics.

When considering the thickness of each fabric, as shown in Table 6, it is interesting to note that the fabric thicknesses seem to correlate with the compression work for each fabric. Fabric 2 was around midway between both fabrics in thickness and compression work. Overall, Figure 32 illustrates a linear relationship between the three fabrics, showing similar spacing in the compression work for each fabric.

Table 6.
Average Fabric Thickness

Test (Standard If Applicable)	Fabric 1: Industry Jersey	Fabric 2: Half Spacer	Fabric 3: Complete Spacer
Fabric Thickness ASTM D-1777-96	0.646 mm	2.744 mm	5.976 mm

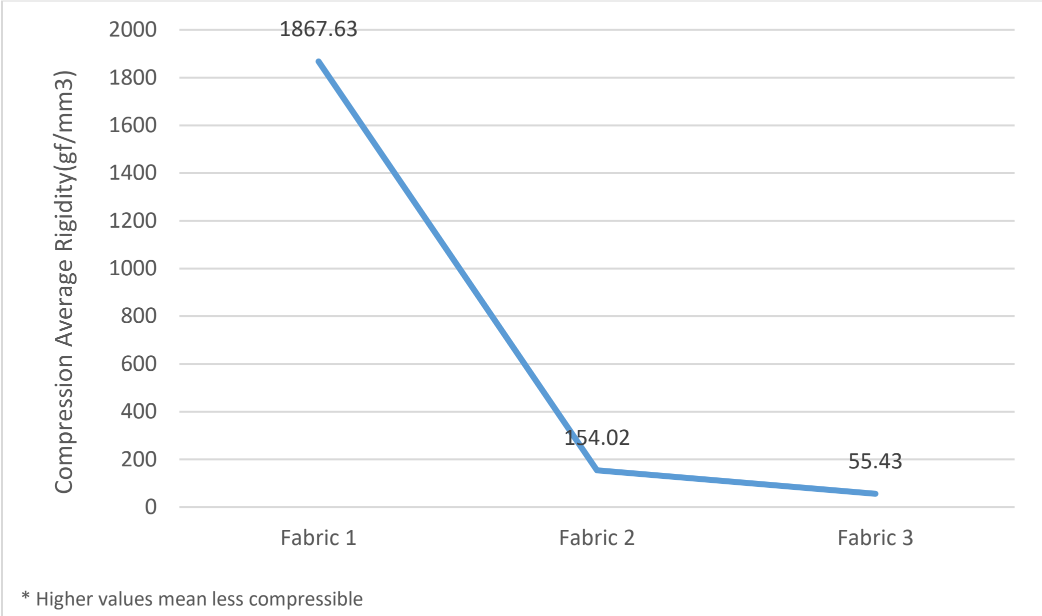


Figure 32. Force needed to compress fabric per mm.

The data show there was a definite difference between the force needed to compress the spacer knit fabrics versus the base layer sample. Fabric 3 was the most compressible fabric, followed closely by fabric 2. When comparing the compression work (See Figure 32) to the compression average rigidity (See Figure 33) of each fabric, it was interesting to find that while fabric 3 had the highest compression work value, fabric 1 required the highest force needed to compress the fabric per millimeter. One consideration is that the fabric was only 0.646 mm, but it is unclear whether the compression average rigidity calculation took these factors into consideration.

Fabric 3, which took the most work to compress, also had the lowest recovery rate. The linear relationship between the three fabrics in compression work (See Figure 32) is also evident in compression recovery rate (See Figure 33).

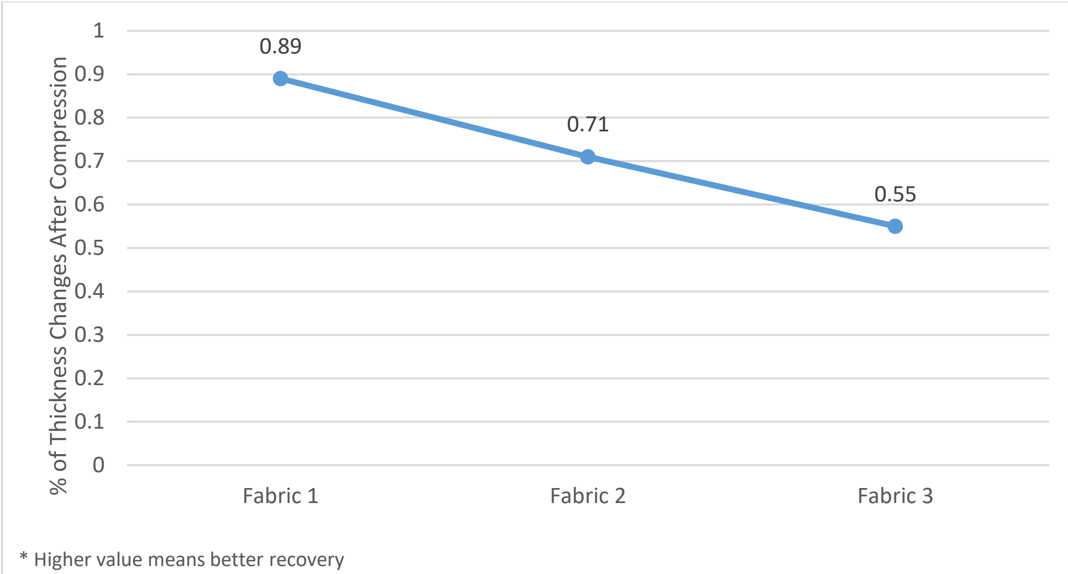


Figure 33. Fabric compression recovery rate.

Surface testing results. Surface testing was based on the roughness and friction of the fabric against probes and wires on the KES-FB4 Surface Tester. This test measured the surface roughness and smoothness in both the length and crosswise direction of the fabric, then took the mean of both directions to calculate the fabric average. With these two surface variables, the test was broken down into MIU and SMD. MIU represents the coefficient of friction. Higher MIU values mean greater resistance, drag, or friction on the fabric surface. SMD reflects the geometric roughness measurement. Higher value means a rougher surface.

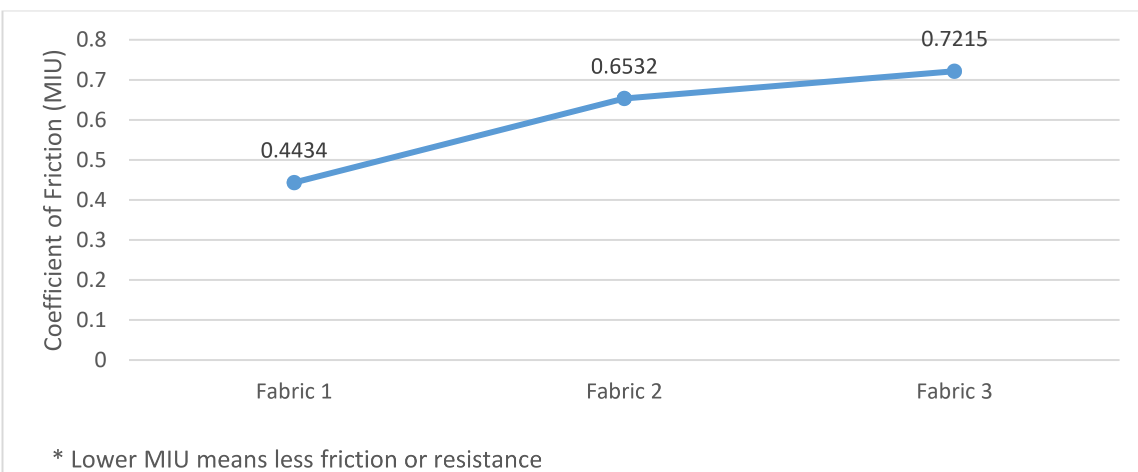


Figure 34. Coefficient of surface friction (MIU) of fabrics.

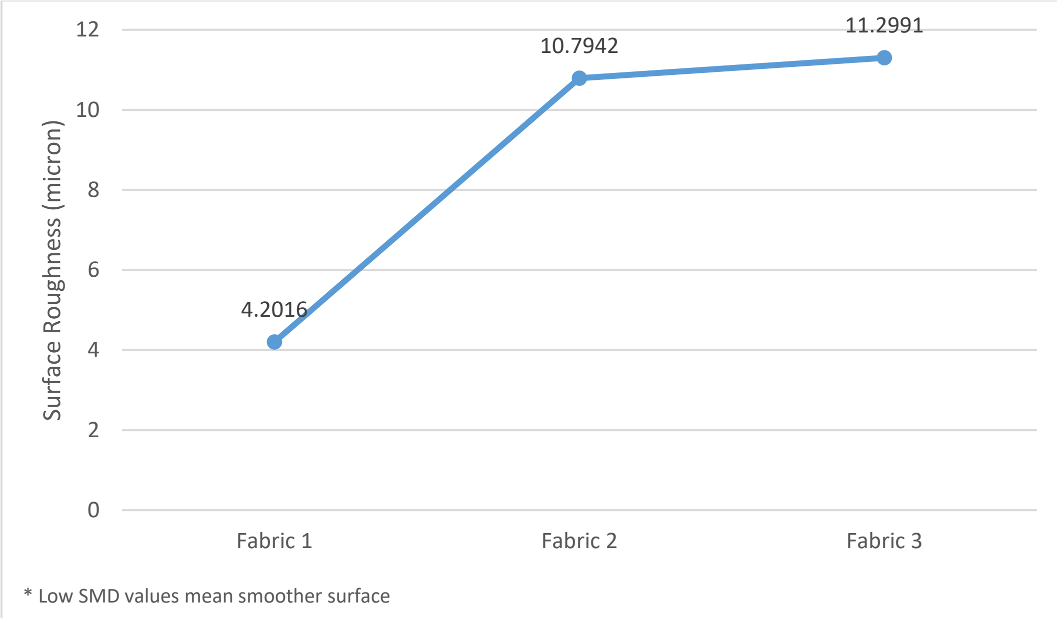


Figure 35. Measure of geometric roughness (SMD) of fabrics.

Figures 34 and 35 illustrate a rise in fabric roughness and friction when comparing fabric 1, which had no spacer fabric, to fabrics 2 and 3, which had spacer fabric. This means that in this test, fabric 1 was the smoothest with the least amount of surface friction. For both variables of surface, fabric 3 had the highest friction and roughness measurements. Fabric 2 was not far behind in its measurements and was more closely measured to the same values as fabric 3 compared to fabric 1. This may point to the conclusion that the spacer knit structure is what was causing the increase in these variables. The increased surface roughness and friction may have been caused specifically by the yarn tucks occurring throughout the spacer structure. Instead of each needle having only one yarn held on it to knit, as when knitting a jersey fabric, the needles knitting a spacer fabric would have two yarns held on to be knit onto the fabric face.

Weight and thickness testing results. Before testing started, weight and thickness measurements were taken after the fabrics had been steamed, as shown in Table 7. This is often referred to as the finished state.

Table 7.
Fabric Thickness and Weight

Test (Standard if Applicable)	Fabric 1: Commercial Jersey	Fabric 2: Half Spacer	Fabric 3: Complete Spacer
Fabric Thickness ASTM D-1777-96	0.646 mm	2.744 mm	5.976 mm
Fabric Weight	220 g/m^2	568 g/m^2	988 g/m^2

After the wear trials were concluded, different areas of the spacer fabric sewn into pants 2 and 3 were measured for changes in thickness. Because a small number of participants used the garments briefly, the garments were not laundered. The decision not to wash the pants removed laundering as a variable. Each pant was measured on the same day after the second round of wear trials. Thickness measurements of the spacer fabrics sewn to the garment fabric were performed to get an average thickness of the padded garment areas before the pants were used. The mean thicknesses of the padding in pants 2 and 3 before and after the wear trials are illustrated in Figures 36 and 37, respectively.

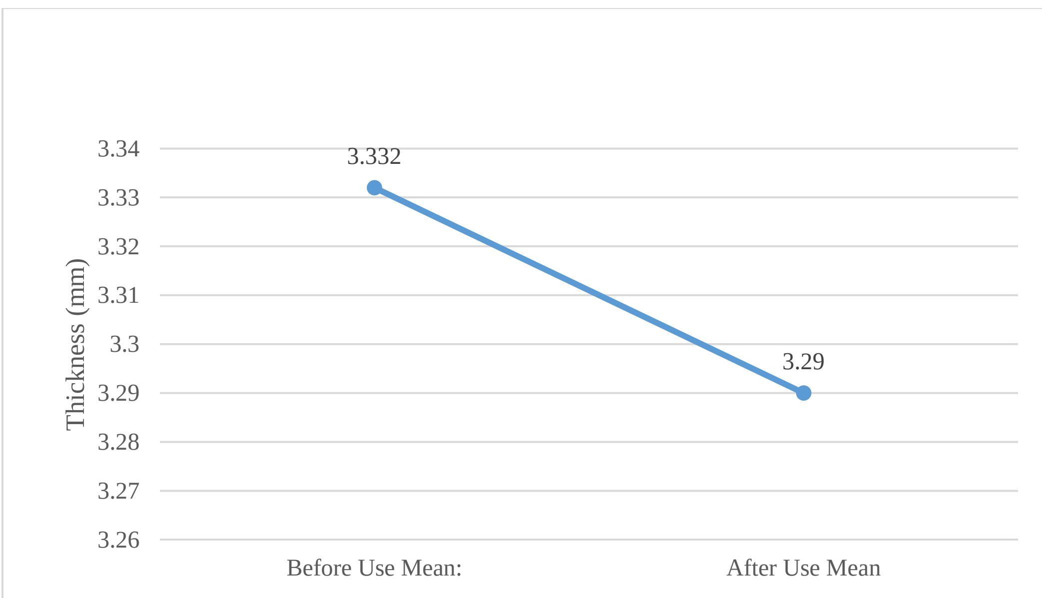


Figure 36. Mean of padding thickness in pant 2 before and after use.

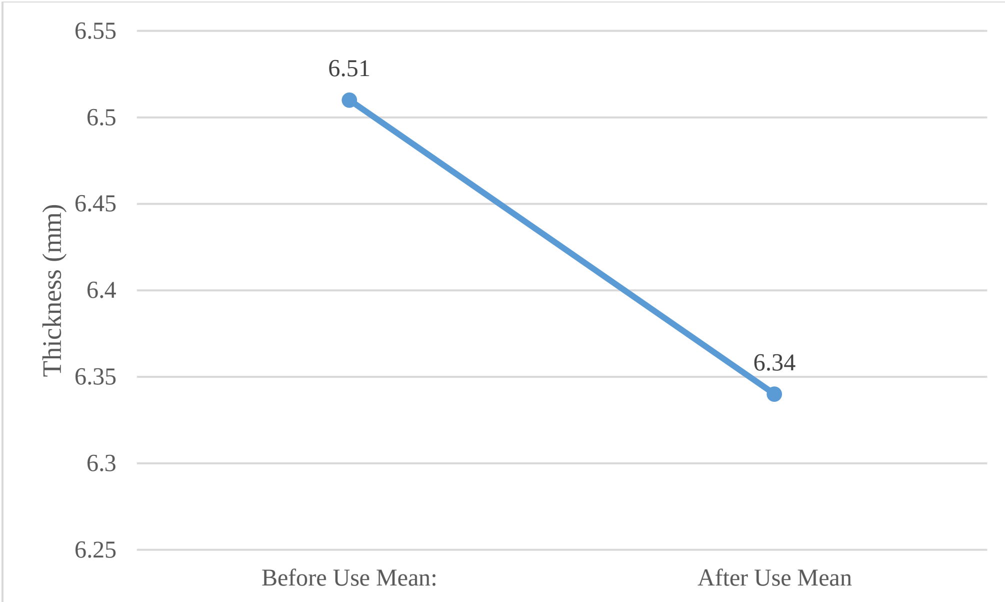


Figure 37. Mean of padding thickness in pant 3 before and after use.

A simple *t* test was performed to ascertain whether the difference in the before and after use padding thickness measurements was statistically significant. For this experiment the following null hypothesis was formed:

H_0. There is no significant difference between the thickness of the fabric before and after use for pant 2.

With a *p* value of 0.27, H_0 could not be rejected, as there was no statistical evidence that there was a difference between the padding thickness measurements for the before and after wear trial usage in pant 2.

For pant 3, the same type of simple *t* test was performed to find whether the difference in the before and after thicknesses was statistically significant. The following null hypothesis was formed:

H_0. There is no significant difference between the thickness of the fabric before and after use for pant 3.

In this test, the *p* value was 0.008, which was below the accepted maximum value of 0.05 needed to reject the null hypothesis. Therefore, H_0 was rejected; in pant 3, there was a statistically significant difference in the padding thickness for the before and after wear trial usage. This difference may be correlated to the low compression recovery rate of pant 3 as shown in Figure 33. However, this difference in thickness may simply be related to the redistribution of fabric throughout the sewn panel as users wore them. Further investigation into the effect of repeated use on fabric thickness and shape would be necessary to draw any conclusions.

Wear Trial Results

Likert scales were used to gauge participants' responses to the different pants and were converted to numbers for each question, meaning each response was converted to a number from 1 to 5 from left to right. For example, the first question about the stiffness of the pants while walking gave participants the option to rate the pants using the Likert scale shown in Figure 27. In this instance, 1 represented *very stiff* and 5 represented *very flexible* with the in between options making up 2, 3, and 4. These numerical values allowed mean ratings to be calculated for each characteristic for each pair of pants and for statistical analysis of these findings. Statistical analysis consisted of simple t-tests to determine if there was a statistically significant difference between two sets of data.

For each of the Likert scale questions, a simple *t* test was performed on the data of two sets of pants or those with padding or no padding. Four *t* tests in total were conducted for each question and the basic layout of the null hypothesis for each test (leaving out the characteristic tested) is shown below:

H_0. There is no significant statistical difference between pant 1 and pant 2.

H_0. There is no significant statistical difference between pant 2 and pant 3.

H_0. There is no significant statistical difference between pant 1 and pant 3.

H_0. There is no significant statistical difference between pants with no spacer fabric (pant 1) and pants with padding (pants 2 and 3).

If the *p* value for these tests was greater than 0.05, the null hypothesis could be rejected. This means there was no significant statistical difference between the two pairs of pants. However, if the *p* value was lower than 0.05, then there could be a significant statistical difference between the two pant groups. If there was no significant difference between the pairs, they were generally not discussed in the data analysis.

Pre-climbing questions. As seen in Figure 38, each pair of pants had a mean rating between somewhat flexible and very flexible. While the figure does show a decrease in rating between pant 1, with no padding, and pants 2 and 3, which had padding, there was not enough of a difference for the difference to be statistically significant. Therefore, the four *t* tests failed to reject any of the null hypotheses, meaning there was no significant difference statistically between the rating of pant stiffness while walking. Participants were asked again about pant stiffness while climbing to see whether different activities and ranges of motion caused a change in their responses.

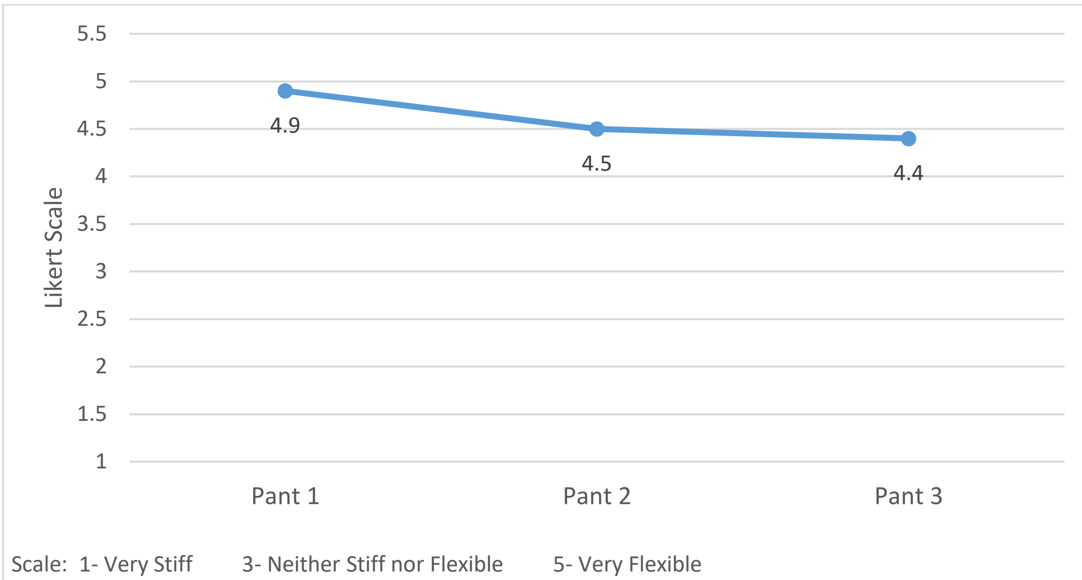


Figure 38. Participant responses to pant stiffness while walking.

Figure 39 shows that in this study, participants found pants 2 and 3 to have the same bulkiness under their harnesses despite the difference in thickness. This may have been caused by the presence of extra fabric padding in the area instead of the thickness of the fabric itself. The *t* tests between pants with no padding (pant 1) and pants with padding (pants 2 and 3) produced results to reject the null hypothesis that there was no significant difference between these two pant groups. Though this proves there was a difference in bulkiness, the ratings for both groups of pants were still positive, indicating the pants were form fitting and not noticeably bulky.

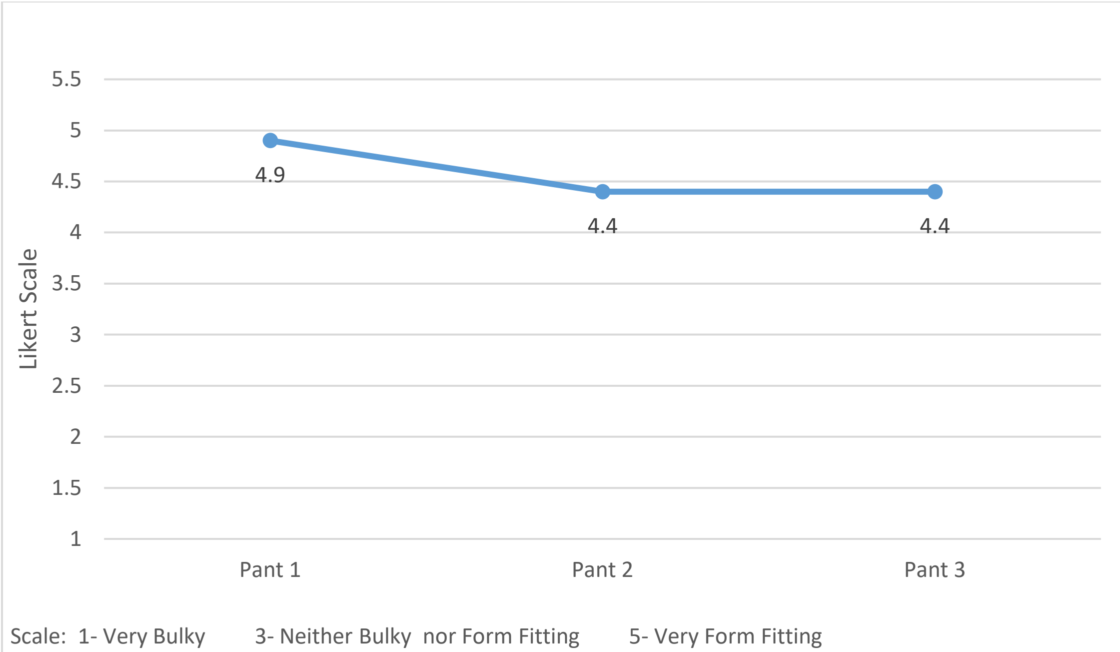


Figure 39. Participant responses to bulkiness of pants.

While the focus of this study was not on thermal comfort, the survey included a few preliminary questions about the temperature of the different pairs of pants while walking and climbing. These questions were added to serve as a possible starting point for future research. These questions also proved to have some of the most rejected null hypotheses of questions in the survey. Figure 40 shows the mean differences between pants 1, 2, and 3. A significant difference between pant 1 and 2 was proved by a simple *t* test with a *p* value of 0.028.

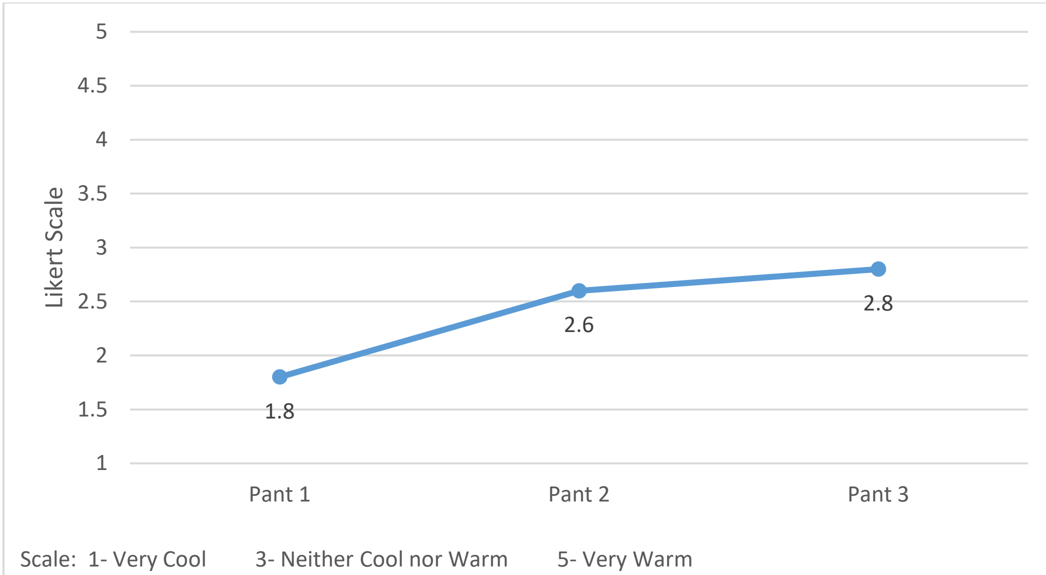


Figure 40. Participant responses to temperature of pant while walking.

Based on the graph and the *t* test results, there was a significant difference between the temperature ratings of pants 1 and 3, with a *p* value of 0.011. With both means being separated by 1.0 point, pant 1 was rated toward somewhat cool and pant 3 was closer to neither cool nor warm. The strongest relationship difference was between pants with padding (pant 1) and pants with no padding (pant 2 and 3) with a *p* value of 0.008. User responses to temperature of pants while climbing were also gathered in an attempt to understand how exercise affected the temperature ratings of the pants. To compare the results of temperature of walking with that of climbing, refer to Figure 45.

In the final question of the pre-climbing portion, users were asked how easy it was to put the pants on and situate them under the harness. Though participants did not get formal direction on how the pants were designed to be worn, a few asked questions while others did not. In the end, the *t* tests did not lead to a rejection of the null hypothesis, leading to the conclusion that there was no difference among the three pants in how easy they were to put on correctly with the harness and padding. Overall ratings in this question indicated all the pants were very easy to put on (See Figure 41).

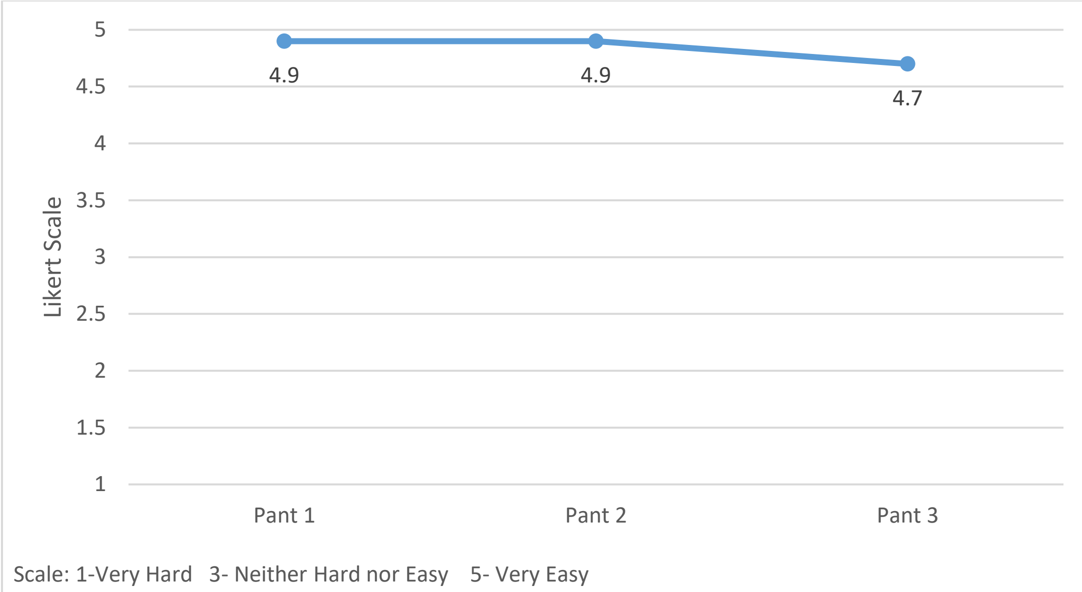


Figure 41. Participant responses to ease of putting on pants correctly with harness.

Post-climb questions. When comparing the mean ratings of stiffness while walking and climbing, shown in Figures 38 and Figure 42, respectively, the values for each pant were the same. This points to the conclusion that participants did not experience a change in stiffness when comparing the two physical activities. Again, there was no significant statistical difference to reject the hypotheses that there were differences in participant responses among the stiffness of pants. These findings point toward participants rating the pants as somewhat to very flexible despite the level of padding or the presence of the spacer fabric for both walking and climbing.

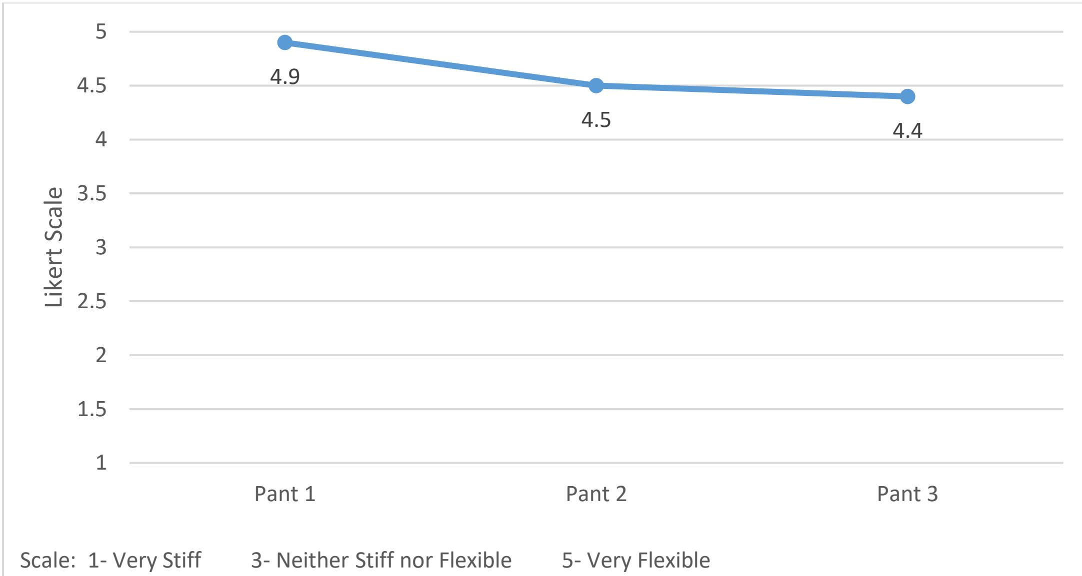


Figure 42. Participant responses to stiffness of pants while climbing.

Similar to the physical hand testing results for surface, where roughness increased between pants 1 and 3 (shown in Figure 35), the user responses mirrored the decrease in fabric smoothness as well (See Figure 43). Statistically, pants 1 and 3 as well as pants with no padding (pant 1) and pants with padding (pant 2 and 3) were both significantly different. Despite these differences in user rating, all pants still scored a mean value above a 4, which would indicate the pants were somewhat smooth. While the relationship of the difference between pant 1 and 3 was just slightly above the necessary p value to reject the null hypothesis at 0.052, the difference between the smoothness rating of pants with padding versus pants without padding was strong at $p = 0.007$.

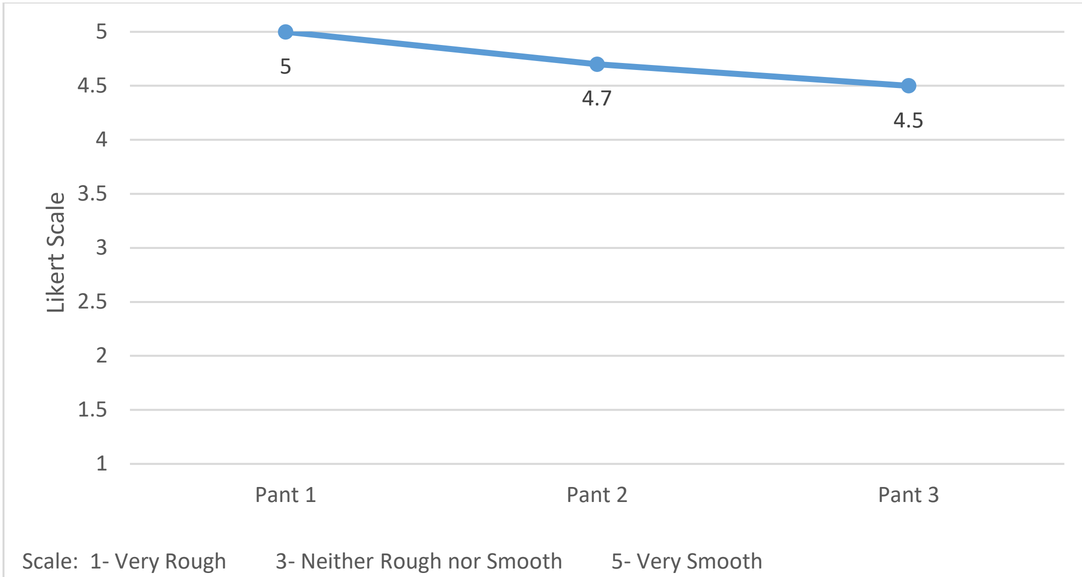


Figure 43. Participant responses to smoothness of pants.

After performing statistical analysis on the data through *t* tests, there was no significant difference among the ratings for the three pairs of pants (See Figure 44). All pants rated between somewhat stretchy and very stretchy. However, the pants with spacer fabric inserts did not out rate the control pants with no spacer.

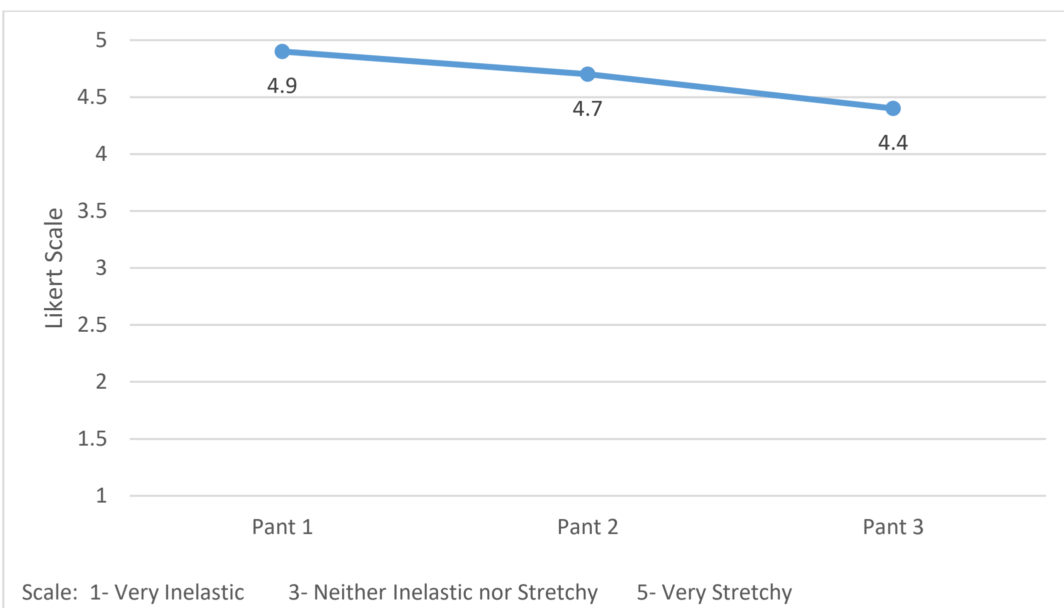


Figure 44. Participant responses to stretchiness of pants.

In the second round of questioning about the temperature of the different pants, surprisingly there was less statistical evidence to point to differences between the pants. In the previous question, shown in Figure 40, *t* tests proved that there was a difference between the temperature ratings between pants 1 and 2, pants 1 and 3, and pants without padding and pants with padding. However, in this later test, the same tests led to a rejection of the null hypothesis that there was no difference between pant 1 and 2 (See Figure 45). This means that statistically, there was no difference in the rating of temperature between pant 1 and 2 while climbing, but there was a difference for the rating while walking. The previous claims that there was a statistical difference between user perceptions of temperature between pant 1 and 3 and pants without padding and pants were still supported.

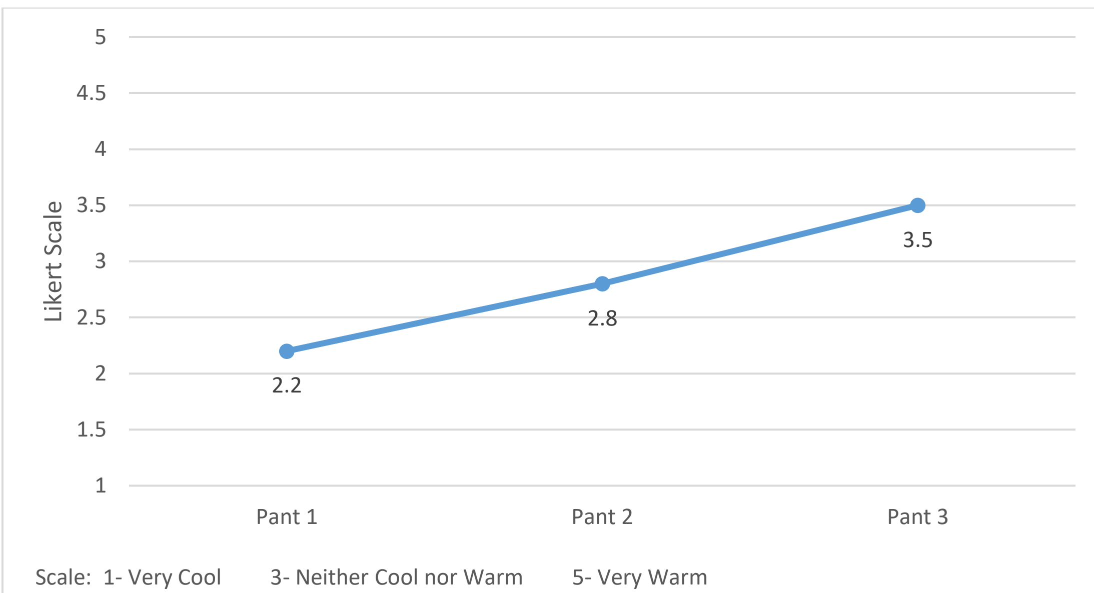


Figure 45. Participant responses to temperature of pants while climbing.

With the data from both temperature questions, *t* tests were performed between the walking and climbing temperature ratings. One example of the null hypothesis for the first pant was:

H_0. There is no statistical difference between the participant responses to the temperature of pant 1 while walking with the temperature of pant 1 while climbing.

The same null hypotheses were used for pants 2 and 3 in the same format. There was no statistical evidence to reject any of these null hypothesis. This led to the conclusion that there was no statistical difference in user responses to temperature in the pants while walking or climbing.

During testing, participants were asked to hang in their harnesses on the wall for 2 minutes. The rating of extended seat comfort was in response to user perceived comfort during those 2 minutes. When performing *t* tests on the results of this survey question, there were some very strong correlations between pants 1 and 3, pants 1 and 2, and pants without padding and pants with padding. The null hypotheses for these three pairs of data were rejected with *p* values <.001. The smallest *p* value ($3.67e^{-8}$) belonged to the *t* test conducted to analyze whether pants without and pants with padding were statistically different. Overall, the data showed that participants indicated pants with padding were far more comfortable in a seated position than those without, with pant 3 providing the most comfort (See Figure 46).

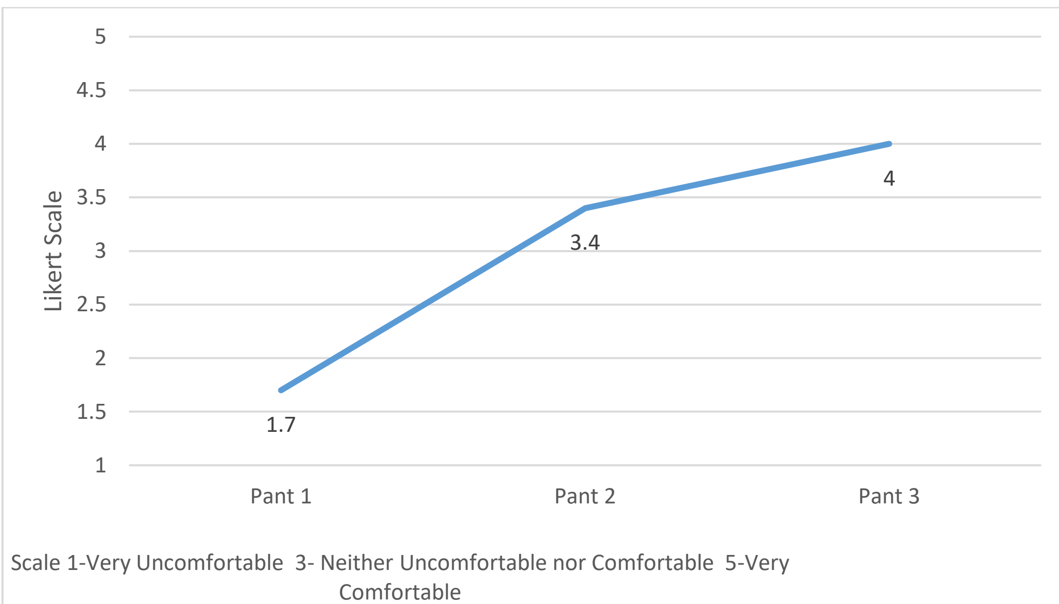


Figure 46. Participant responses to extended seat comfort in harness.

Overall rating and final questions. Displayed in Figure 47, pants 2 and 3 were rated higher than pant 1 in overall rating of pants, but pant 3 rated the highest overall. When statistically analyzing this question through *t* tests, there was the strongest, significant difference in user responses between pants 1 and 3. With a *p* value of 0.0007, this relationship between pants 1 and 3 was the strongest difference between two sets of data in the entire survey. There was also a significant statistical difference between pants 1 and 2, with a *p* value of 0.014, rejecting the notion that there was no significant difference between the two pants. Consequently, the null hypothesis between pants without padding (pant 1) and pants with padding (pants 2 and 3) was also rejected with a *p* value of 0.002. As the first of several questions on overall perceptions by participants, this question addressed each pant individually while later questions asked the participants to weight their opinions of the pants against each other.

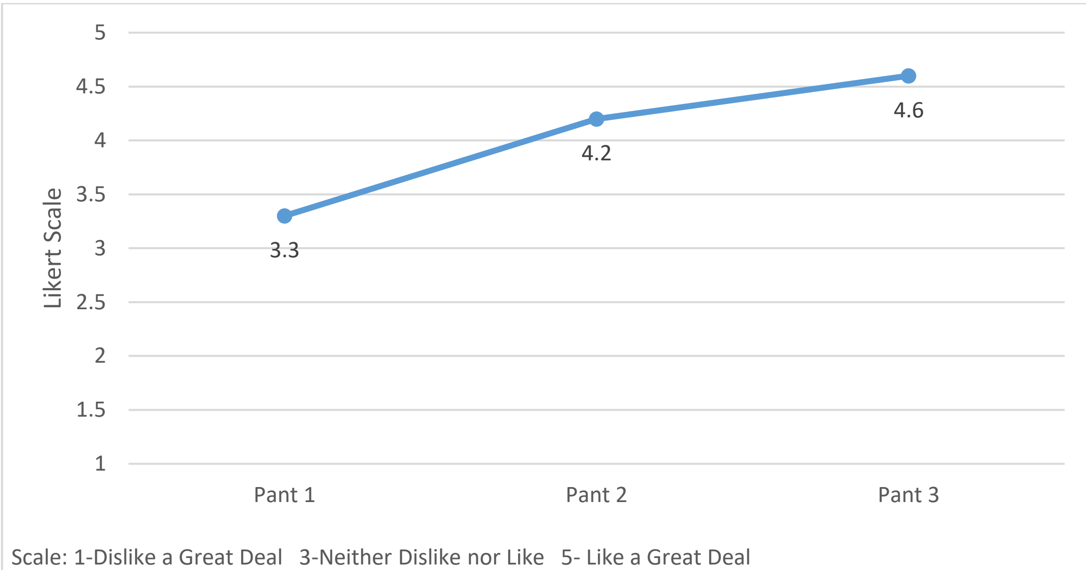


Figure 47. Participant responses to overall perception of pants.

Though the previous questions gave numerical values to different aspects of the pants according to the consumers, an additional question was needed to ascertain which pant they would actually buy. Instead of rating the pants individually, participants had to choose among the three pants. This question provided a better understanding of consumer buying behavior with this product in addition to their responses to different aspect of the pants. When comparing which pants they were most and least likely to purchase, shown in Figures 48 and 49, to the overall rating of the pants shown in Figure 47, results show pant 3 rated most liked while pant 1 was the least liked. Having both sets of data between overall perception of the pants and which the participants were most likely to buy showed a stronger gravitation by participants toward pant 3, though pant 2 was not far behind in overall rating and purchase options.

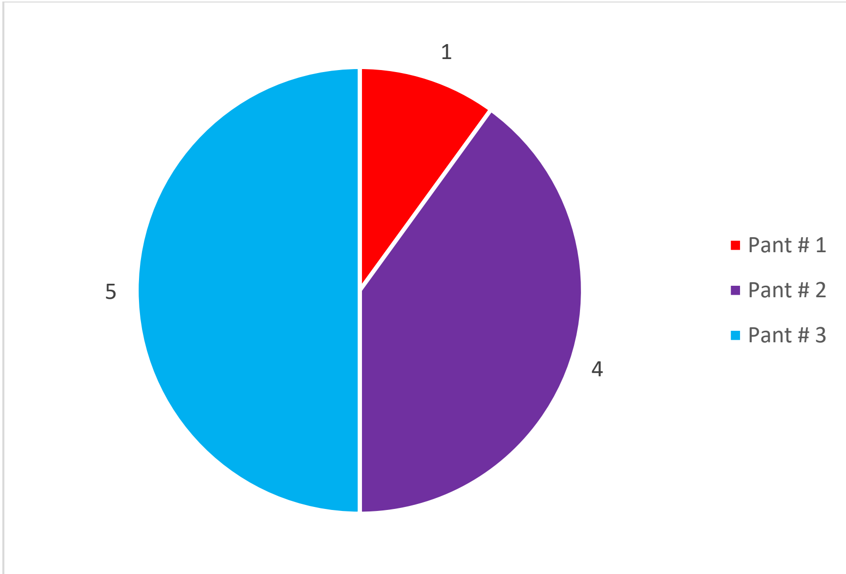


Figure 48. Participant responses for pant they were most likely to purchase.

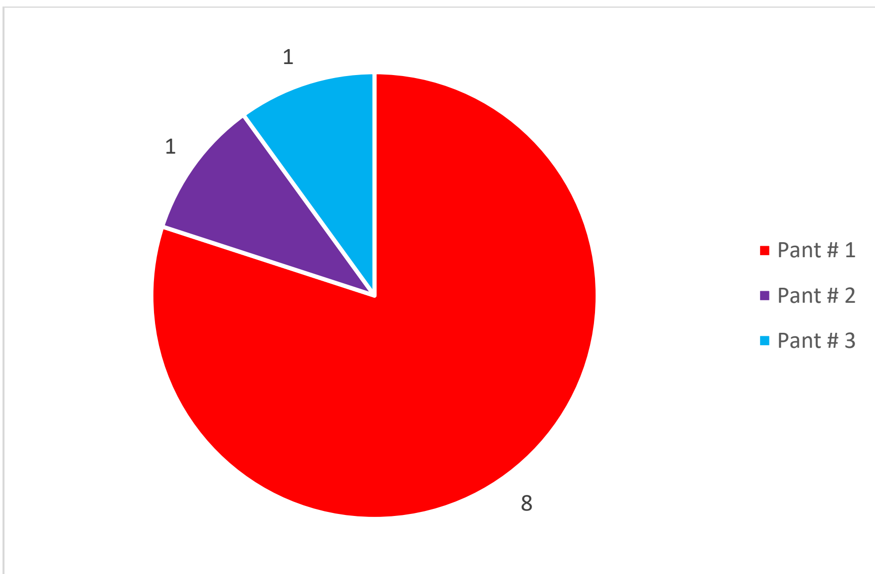


Figure 49. Participant responses for pant they were least likely to purchase.

After the participants decided which pant they were most and least likely to purchase, they were asked to answer a question as to why or why not. Participants could select all characteristics of the pant that would have affected their buying preference. These questions were aimed at understanding consumer preferences (See Figure 50).

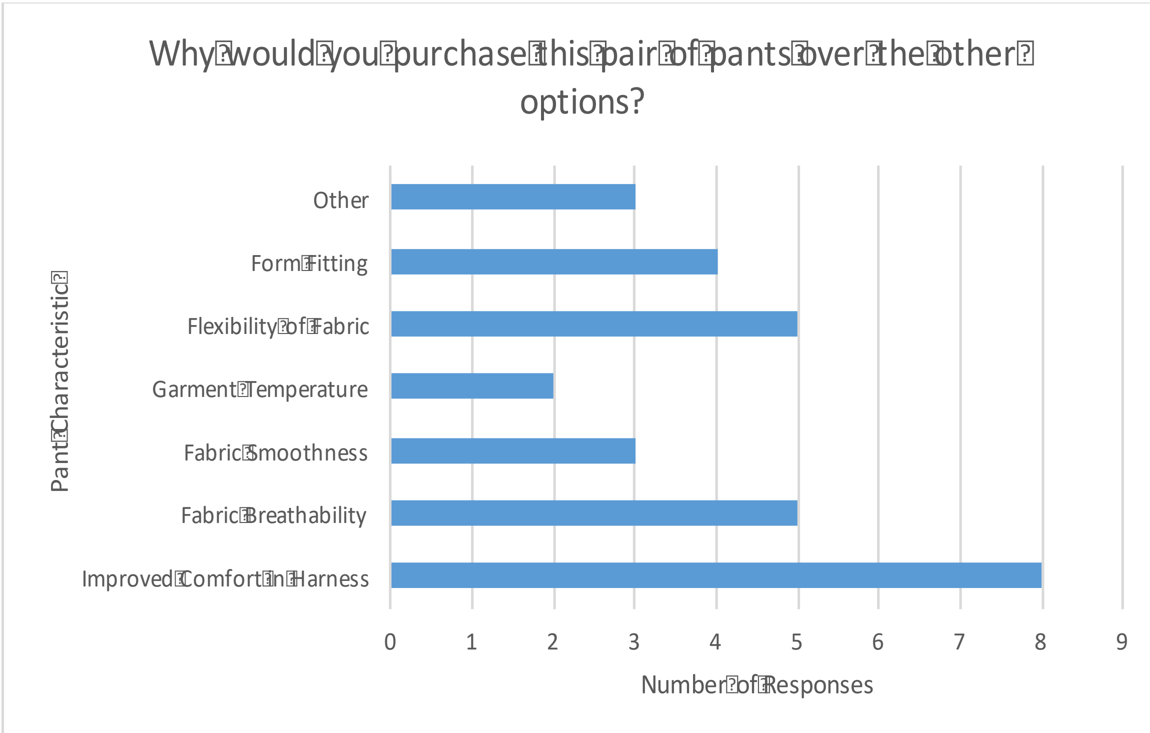


Figure 50. Participant responses to why they would purchase that pair of pants.

The top three responses were improved comfort in harness, fabric breathability, and flexibility of fabric, with the most important being improved comfort in harness. These results were a mixture of chosen answers from a list as well as written in responses. This answer may have been influenced by the fact that the padding was designed to improve this area of comfort, so it could be what participants focused on. It could also be that their experience with comfort was the thing that stood out most in their minds, and therefore they responded as such. Either way, comfort was the main factor in the reason behind their purchase preferences. However, participants were not asked what they would be willing to pay for pants with padding. Helpful insight into consumer perceptions and purchasing decisions was gained from the "other" comments that were added. Three participants gave more in-depth reasoning behind their decision. "Other" responses were as follows:

- "Improved comfort and breathability were both equally important."
- "All pants were uncomfortable when sitting in them, the ones with the padding made it more bearable but didn't eliminate the discomfort. I really like the feeling of the first ones [pant 1], just felt like I was wearing nothing and nothing was restricting my motion while climbing."

- "For the climbing I am doing, I am not yet spending a significant time seated in the harness, so a little extra padding is nice but I don't necessarily need more padding even though number 3 was definitely most comfortable."

Following this question, participants responded to which pant they were least likely to purchase and why. As seen in Figure 51, comfort was also the major factor in their rock climbing pant decision. Because both questions listed the "comfort in harness" option, it could mean user comfort while walking, climbing, or hanging in harness. Based on the above comments about how often participants were sitting in their harnesses and how the padding affected their seated comfort, participants may have been speaking more of seated comfort, but it could also mean overall comfort as well. Because comfort in a certain activity or position was not mentioned, the question must then be applied to just overall user comfort when wearing a harness.

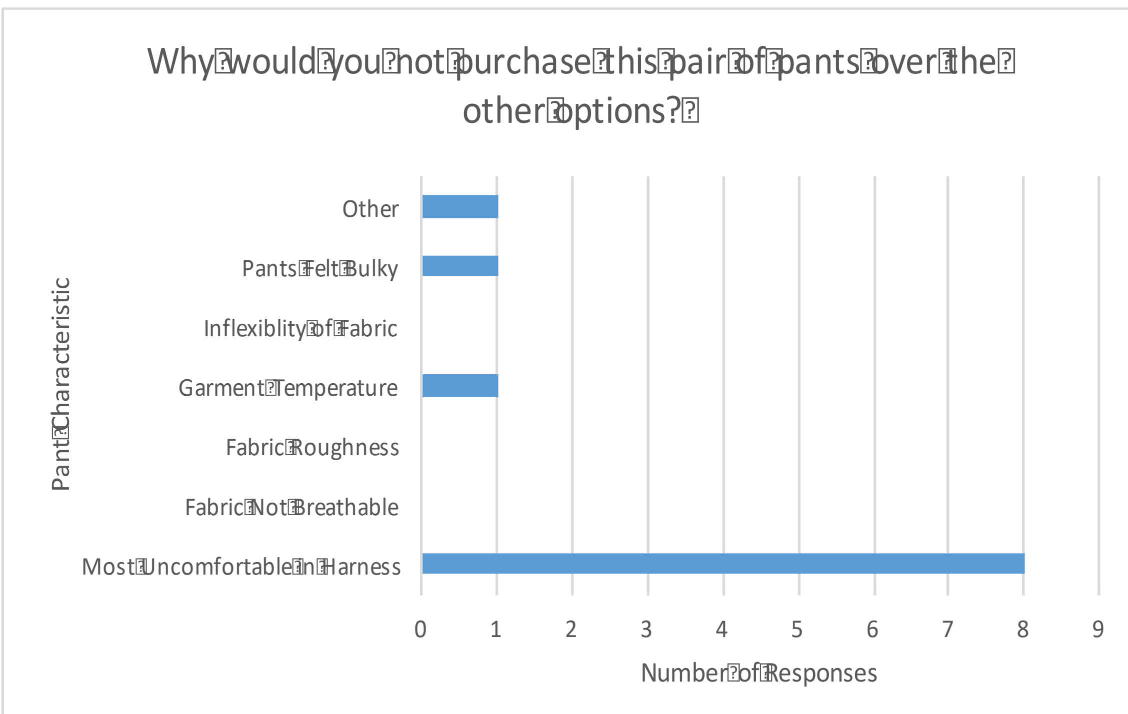


Figure 51. Participant responses to why they would not purchase that pair of pants.

The only "other" response for why a participant was least likely to purchase pant 2 was as follows: "These [pant 2] were alright but just didn't have the mobility and free feeling of the first ones [pant 1] but also didn't have the comfort of the third one [pant 3]." In this instance, the participant expressed that pant 2 did not excel in either mobility or comfort, and therefore was least likely to be purchased by this participant. It should be noted that this participant was the only one to indicate being least likely to purchase pant 2, while 80% were least likely to purchase pant 1. Furthermore, in order to gain insight into consumer consumption patterns, participants were asked what pants they usually wore rock climbing (See Figure 52).

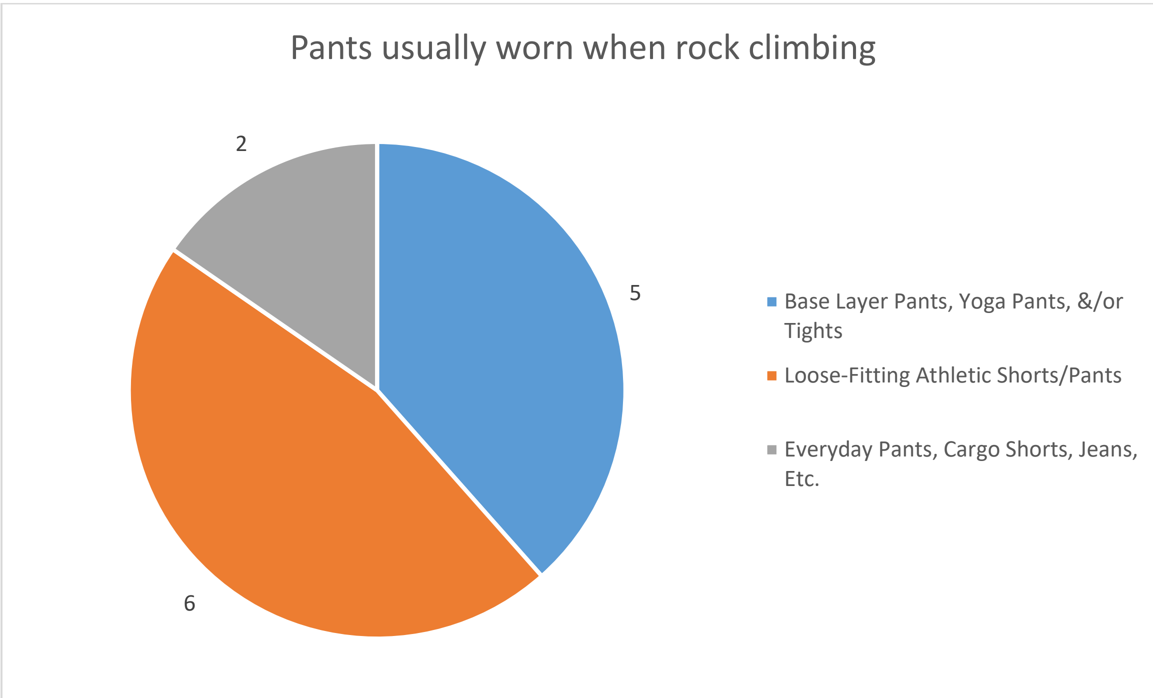


Figure 52. Participant responses for normal kind of pant for rock climbing.

This multiple choice question was included for consumer research in furthering this project or further product development in this market. With little research on what rock climbers tend to wear while participating in the activity, data on the pant they normally rock climb in could help researchers create desirable products. Now knowing that the majority of people wear either loose fitting athletic shorts/pants or tight fitting pants, better products can be designed.

The final question of the survey asked participants to “please provide any further information that you feel would be influential in furthering this product or study.” Additional comments were as follows:

- “Great Shorts! I would buy a pair in both the second and third options depending on where and when I was climbing. Summer I would use number one and on cooler days I’d use pants number three.”
- “I think the first pair are great for sport climbing/single pitch stuff where you don’t have to wait [(*sic*)] the harness a lot but you want that free range of motion. The third ones would be great for long multi pitch climbing where you have to sit in your harness a lot.”
- “Waist padding in #3 was good, but in all 3 pants, the leg padding needed to be a little wider/taller (perhaps more padding than in the waste [(*sic*)]). Overall great comfort and flexibility; I hardly noticed I was wearing them.”
- “I look for comfort, flexibility, and versatility.”
- “They are pretty awesome!”

Wear trial observations. During testing, several observations were made about pant usage, participants expressed opinions that they did not note in their survey responses, and in one case one subject added his own extra test cycle to the wear trials. Though some of these observations were outside the specific scope of this research, they are important to record for future research and add context to some of the findings. These observations were as follows:

- After all testing was completed and all forms and answers submitted, one participant tested pant 3 with his personal harness to determine whether pant 3 added comfort to his climbing experience. His personal harness had built-in padding where the programming harnesses were just nylon. He climbed one climb during this independent testing session and hung in a seated position for 2 minutes. Afterward, he noted that pant 3 still made a positive difference in his overall comfort while climbing.
- Three participants expressed a desire for pants that only had padding in the legs. They conveyed that they were not used to how high on the body the pants were and felt they were more likely to wear pants 2 and 3 if they fit at the hips and not at the waist.
- The four female participants all wore the pants higher on the body and, thus, the padding tended to be more securely situated under the harness when climbing. Having the pants higher meant the harness sat toward in the middle of the padded

area instead of at the top as it did with several males. The male participants wore them lower, which, in turn, put the padding lower on their legs and not directly where the harness fit. It should be noted that three male participants wore loose gym shorts over the pants, so observations on where the harness sat on the padding were not possible.

- Also mirrored in the additional comments in the survey provided by two subjects, two participants spoke openly about how they felt that pants 2 and 3 had different uses within rock climbing. These participants both noted that if they were taking part in a certain type of climbing where they would either be partially or wholly suspended in their harness for an extended period of time, they would wear pant 3. If they were taking part in an activity where they were in a warmer environment or they did not think they would be fully suspended in their harness for any extended period of time, they would wear pant 2.

CONCLUSIONS

Based on the participants' responses, pant 3 with full fabric spacer was the best pant for rock climbing applications. In wear trials, users claimed that both pants with spacer fabrics (pants 2 and 3) increased extended seat comfort in a harness; also, nine out of the 10 participants indicated they would most likely purchase either pant with spacer fabric padding over the pant without spacer fabric for rock climbing purposes. This was supported by the ratings for extended seat comfort where pant 3 was rated most comfortable. Participants also rated pant 3 as being flexible, stretchy, and form-fitting despite being the pant with the thickest padding. Pant 3 rated highest on the overall perceptions scale with the majority of participants stating they were most likely to purchase pant 3. These findings point to the conclusion that pant 3 was the best for a rock climbing application in terms of improving user sensory and seated comfort.

While pant 3 with the full spacer fabric was the favored pant in the wear trials, the fabric (fabric 3) proved to be very different than the half spacer fabric (fabric 2) in many aspects of physical testing and fabric characteristics. Physical testing of fabric hand for fabric surface and compression showed the fabric results were consecutively progressive from fabric 1 to fabric 3. In terms of surface roughness and smoothness, fabric 1 tested lowest on each scale, meaning it was the smoothest and least rough, and fabric 3 tested on the highest of each scale, making it the roughest and least smooth. Fabric 2 tested in between the two other fabrics on each test. This trend of fabric 1 being low, fabric 3 being high, and fabric 2 being in the middle continued with both weight and thickness. However, during burst strength testing, fabric 3 exceeded the machine's psi capacity, and fabric 1 took a higher psi than fabric 2 to burst.

With the results of the physical hand testing in mind along with the wear trial results, fabric 2 was the best fabric of those tested for athletic applications as a whole. In this fabric, the combination of spacer and jersey knit structures allowed the fabric to cushion the body while still exhibiting similar characteristics of the base layer fabric. In physical testing, it was closer in smoothness and roughness to the base layer fabric currently being sold but still had some of the compression abilities of the spacer fabric that increased user comfort while rock climbing. In wear trial surveys, pant 2 was rated as having more stretch, less stiff, and cooler when compared to pant 3. Four out of the 10 participants indicated they were most likely to purchase pant 2. Additional user comments pointed toward this half spacer fabric being better suited for warmer environments as participants believed it was more breathable and cooler than the full spacer fabric.

In the end, this study represents preliminary research into these spacer fabrics being used in base layers to increase user comfort in weighted and athletic applications. More research into the different fabric properties such as laundering and moisture management would be necessary to better understand their use in athletic apparel.

FUTURE WORK

While this research was designed to better understand the use of spacer fabrics in athletic apparel, there are research areas as well as future uses for this fabric that need further investigation.

In this research, a jersey and spacer fabric was created to be an intermediate level between full spacer panels and jersey panels. This fabric was knitted with two rows of spacer knit followed by two rows of jersey knit, but that was just one way for the spacer fabric to be inserted into the tube. For example, researchers could knit four rows of spacer knit followed by two rows of jersey, or vice versa. As long as there are even rows of each knit structure, the machine can knit a plethora of different spacer and jersey combination fabrics. Future research could be done into these different structure combinations in padding applications or the effect of these jersey sections on rigidity, strength, breathability, and moisture management. Research into how the fiber content of the yarn and the fabric thickness could affect these characteristics could also be done as well. Furthermore, testing different varieties of spacer fabrics against a variety of foams and other three-dimensional composite and laminate materials to find future uses would be important. All of these findings could assist product developers and manufacturers in reducing their use of non-recyclable materials and replacing them with a comparable or better performing spacer fabric.

During the construction of the padded pants, sewing the spacer fabric into the base layer garments proved difficult. The differences in fabric thickness and stretch often made sewing the spacer fabric to the jersey base layer fabric result in a puckering when not on the body. Once on the body, the base layer stretched over the spacer fabric so that it laid flat, but more research should be done into better methods of inserting spacer fabric into garment such as the use of velcro, different adhesives, or even pockets. Seamlessly knitting the spacer fabric into the garments would be the best solution. However, because of spacer fabric shaping difficulties and knit machine gauge differences, the WholeGarment® flatbed machines cannot produce the same quality of jersey knit fabric that is being produced on higher gauge machines. Higher gauge machines would eliminate this problem in the future, but at this time there are no WholeGarment® machines at this gauge. One solution instead of seamless padding could be to use a pocket in the garment into which the user can insert the spacer fabric in the desired area, as the spacer fabric could be knit specifically to create a closed spacer fabric item that fits perfectly in its intended pocket.

In addition to research into fabric insertion as well as fabric development and their importance in creating a better sportswear spacer fabric, consumer-based product development strategies and research could create better target markets for this fabric. Possible future uses include bike shorts padding, equestrian apparel, gardening pants with built-in knee padding, bra padding, padded socks, and padding integrated into the shoulders and hips of backpacking clothing. There may also be opportunities to incorporate spacer fabrics into apparel for the aging population to cushion the body against falls or padding for wheelchairs.

Finally, research into how these flatbed spacer knit fabrics react to laundering and repeated use would help future developers know how the fabric responds to wear and tear and best practices for care. Such studies would aid in predicting fabric longevity and create an opportunity to make longer lasting fabrics and enhanced performance products for consumers.

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APPENDICES

Appendix A: Institutional Review Board- Human Wear Trial Forms

Informed Consent Participation Form

North Carolina State University
INFORMED CONSENT FORM for RESEARCH
Title: Spacer Knit Fabrics in Athletic Applications
Principal Investigator: Erin Doran
Faculty Sponsor: Dr. Andre West

What are some general things you should know about research studies?
You are being asked to take part in a research study. Your participation in this study is voluntary. You have the right to be a part of this study, to choose not to participate or to stop participating at any time without penalty. The purpose of research studies is to gain a better understanding of knit structure applications in athletic apparel.
You are not guaranteed any personal benefits from being in this study. Research studies also may pose risks to those that participate. In this consent form you will find specific details about the research in which you are being asked to participate. If you do not comprehend this form, it is your right to ask the researcher for clarification or more information. If at any time you have questions about your participation, do not hesitate to contact the researcher(s) named above. A copy of this consent form will be provided to you.

What is the purpose of this study?
The purpose of the study is to test types of padding and knit structures use in athletic apparel, namely rock climbing pants. The main purpose is to better understand if these knit fabrics have any effect on user comfort.

What will happen if you take part in the study?
If you agree to participate in this study, you will be asked to complete 6 rock climbs at the NC State University Recreation Rock Wall. Before participation begins, you will be asked to provide evidence that you are belay certified. Using the NC State issued “Misty Mountain rock climbing alpine harness”, you will be asked to test 3 different pairs of pants by climbing 2 climbs in each pair of pants. While wearing each pair of pants, you will be asked to sit in your harness approximately 10 feet above the ground for two minutes before finishing the climb. After testing each pair of pants, you will be asked to fill out a questionnaire about your comfort in each of the 3 pair of pants. This questionnaire will be presented and asked to be filled out 3 separate times, after each pant is tested. You will then be asked which pair of pants you found most comfortable after testing all 3. During this study, photographs may be taken to better illustrate the use of the pants in these wear trials. The faces of participants will be edited out of the final pictures using Photoshop, and only Erin Doran will have access to the original, unedited photos. This study is anticipated to take a maximum of 90 minutes.

Are there any inclusion criteria for this study?
Participants in this study must be able to provide belay certification cards from outside organizations to help ensure the safety of all participants. Please initial to indicate that the following criteria are met by you. If the following criteria are not applicable to you or you cannot initial next any of the criteria, please tell the testing administrator and you will not be asked to participate in this study.
_______ I am a belay certified rock climber and can provide a certification card.
_______ I am over 18 years old. ID provided
_______ I have been rock climbing for at least 6 months.
_______ I have climbed at least 2 times at a level of 5.5 or above in the past month.
_______ I believe I am comfortable and capable of climbing six 5.5+ climbs of my choosing for this test.

Risks and Benefits
There are minimal risks associated with participation in this research. The risks associated with this study are related to indoor rock climbing in a gymnasium. These risks may include but are not limited to: abrasions, lacerations, falling and hitting the rock or the padded ground, objects falling from the wall onto you, muscle soreness and fatigue, various soft-tissue injuries, and possible anxiety or nervous feelings towards the height aspect of rock climbing. These risks are managed and minimized having participants who have rock climbing experience, the knowledge of how to properly belay, and know how to tie their harnesses into the safety ropes. Safety checks will also be mandatory between climber and belayer before every climb. This helps mitigate the risk of falling due to belayer or a climber’s inability to tie the proper knots for the activity. As a former rock wall supervisor and rock climbing teaching assistant at this rock wall, Erin Doran, the investigator, will also be overseeing that the safety protocol for the wall is followed

to help minimize the risk of injury. There will also be University Recreation Rock Wall staff and/or a Health and Exercise study instructor present at all times to provide additional safety enforcement and assistance. Participants will also have the opportunity to choose which climbs they complete, but are greatly encouraged to climb well below their highest level of performance. Climbing “easy” routes will help minimize the risk of soft tissue injuries due to over-exertion. Between each pant testing period, climbers can take rests and breaks whenever needed. At any point, if participants feel uncomfortable in this study, they are encouraged to let the study investigator, Erin, know and will be excused from the study.
There are no direct benefits to your participation in the research. The indirect benefits are the furthermost of knowledge in the use of spacer knit fabrics in the athletic apparel market and the understanding of human comfort and its relationship to apparel in weighted environments.

Confidentiality
The information gathered in this study will be kept confidential to the full extent allowed by law. Data will be stored securely in Erin Doran’s home and on her locked, personal, laptop computer. No reference to your name, face, or ability will be made in oral or written reports which could link you to the study.

Compensation
For participating in this study, you will not receive any compensation. If you withdraw from the study prior to its completion, you will not receive any compensation or be penalized in any way.

Emergency Medical Treatment
If you are hurt or injured during the study session(s), the researcher will contact the University’s emergency medical services at 515-3333 and/or 911 for necessary care. There is no provision for free medical care for you if you are injured as a result of this study.

What if you are a NCSU student?
Participation in this study is not a course requirement and your participation or lack thereof, will not affect your class standing or grades at NC State.

What if you are a NCSU employee?
Participation in this study is not a requirement of your employment at NCSU, and your participation or lack thereof, will not affect your job.

What if you have questions about this study?
If you have questions at any time about the study itself or the procedures implemented in this study, you may contact the researcher, Erin Doran, at ebdoran@ncsu.edu or at her cell phone: 336-413-7741.

What if you have questions about your rights as a research participant?
If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Deb Paxton, Regulatory Compliance Administrator at dapaxton@ncsu.edu or by phone at 1-919-515-4514.

Consent to Participate
“I have read and understand the above information. I have received a copy of this form. I agree to participate in this study with the understanding that I may choose not to participate or to stop participating at any time without penalty or loss of benefits to which I am otherwise entitled.”

Subject's signature____ Date _________________

Investigator's signature_____________________________________ Date ____________________

Health and Emergency Information Participation Form
Health Form & Emergency Information:
The purpose of this form is to verify that to the best of your knowledge, you are physically fit and healthy enough to take part in this study. It also gives basic emergency information should an incident occur. Please fill out the below information honestly to the best of your knowledge. As you are in a certified climbing gym where you have already filled out wavers and emergency contact information, this form is just to ensure you know what physical activity will be occurring during this study. This will help you determine if you feel you are prepared and able to participate in this study.

THIS STUDY WILL INCLUDE THE FOLLOWING PHYSICAL ACTIVITIES:
Rock Climbing on 30-foot rock wall a multitude times within an hour
Taking announced falls while on belay and at a safe distance from the ground
Hanging in a climbing harness for no longer than 5 minutes
Walking to and from the bathroom to put on a set of pant samples
Stretching and/or warming up or cooling down for climbing related activities

NAME OF PERSON(S) TO CONTACT IN CASE OF EMERGENCY:

Name: ____

Phone: (daytime) _________________________
(cell)_________________________

Relation: ____________________________________

I understand that this form will not be shared with anyone else. I have read the above description of the physical activates occurring in this study, believe I am capable of participating, and understand I can ask for elaboration on any of the information above with Erin Doran at any time. This form will be kept in Erin Doran's possession will not be distributed unless to medical professional in case of emergency. I give Erin Doran permission to give this form and any other pertinent medical information to those medical professionals should a medical emergency occur. I understand that it is my responsibility to determine if I am physically able to participate in this study. I also consent to acting and conducting myself in a way that is safe and respectful of others in this study.
Date:_________
Please print your name: ____
Please sign your name: ____

Photography Consent Form for Participants
Consent & Recording Form

I agree to participate in the study conducted and recorded by the Erin Doran for her thesis research at North Carolina State University.

I understand and consent to the use of the photography by Erin Doran. I understand that the information and visual aids collected are for research purposes only and that my name and image will not be used for any other purpose. Erin is the only personal who will have access to the photos before editing. Erin will use Photoshop to alter photos so that the people in the photos are not identifiable.

I understand that participation in this study is voluntary and I agree to immediately raise any concerns or areas of discomfort during the session with the study administrator, Erin Doran.

Please sign below to indicate that you have read, understand, and consent to the outlines set forth in this form and that any questions you might have about the session have been answered.

*Date:*__________
Please print your name: ____
Please sign your name: ____

Appendix B: Surface Friction and Geometric Roughness Test Data

Property	Fabric 1	Fabric 2	Fabric 3
Surface Friction (20gf/cm):MIU (-) [a]	0.4434	0.6532	0.7215
Roughness: SMD (micron) [b]	4.2016	10.7942	11.2991

[a] Lower MIU corresponds to less friction or resistance and drag
[b] Low SMD values indicate a smoother surface

	MIU [A]		**MMD [B]**		**SMD [C]**	
Sample ID-Replicate	Coefficient of Friction		Mean Deviation of MIU		Geometric Roughness (micron)	
	(L)	(C)	(L)	(C)	(L)	(C)
Fabric 1 -1	0.4395	0.4225	0.0251	0.0091	7.5096	0.803
-2	0.4572	0.4301	0.0218	0.0083	7.5246	0.7363
-3	0.4807	0.4305	0.0193	0.0071	7.9365	0.6995
Avg.	0.4591	0.4277	0.0221	0.0082	7.6569	0.7463
L + C	**0.4434**		**0.0151**		**4.2016**	
Fabric 2-1	0.7261	0.5821	0.0692	0.1379	12.2746	10.3874
-2	0.7159	0.5939	0.0678	0.1258	10.8109	8.9249
-3	0.7028	0.5981	0.0701	0.1427	11.9797	10.3879
Avg.	0.7149	0.5914	0.069	0.1355	11.6884	9.9001
L + C	**0.6532**		**0.1022**		**10.7942**	
Fabric 3 -1	0.7148	0.7149	0.0742	0.0457	13.5506	6.3254
-2	0.7139	0.7257	0.0742	0.0404	18.072	7.0604
-3	0.7218	0.7376	0.0822	0.0564	15.9985	6.7879
Avg.	0.7168	0.7261	0.0769	0.0475	15.8737	6.7246
L + C	**0.7215**		**0.0622**		**11.2991**	

Note: L = lengthwise direction; C = crosswise direction
[a] Values from 0 to 1 with higher values corresponding to higher friction.
[b] Higher value corresponds to larger variations of friction.
[c] Higher values mean a geometrically rougher surface.

Appendix C: Fabric Compression Test Data

Variable	Unit	Definition
Fabric Thickness (T)	mm	Thickness under heavy touch (41 gf applied)
Compression Work (CW)	gf/mm	Works needed to compress the sample Higher values mean harder to compress.
Compression Recovery Rate (CRR)	n/a	Percentage of thickness changes after being compressed. Higher values mean better recovery.
Compression Average Rigidity (CAR)	gf/mm^3	Forces needed to compress per mm. Higher values mean less compressible.
Recovery Average Rigidity (RAR)	gf/mm^3	Forces reflected during recovery per mm. Higher values mean better recovery.

Sample	T (mm)	CW (gf*mm)[a]	CRR[b]	CAR(gf/mm^3)[c]	RAR (gf/mm^3)[d]
Fabric 1	0.54	309.53	0.89	1867.63	1150.84
Fabric 2	2.77	2109.15	0.71	154.02	180.41
Fabric 3	5.84	4771.94	0.55	55.43	95.52

[a] -Higher values mean fabric is harder to compress
[b] -Higher values mean better recovery
[c] -Higher values mean less compressible
[d] -Higher values mean better recovery

Appendix D: Padding Fabric Thickness Measurement Data.

Spacer Fabric Thickness when Sewn into Pants 2 & 3

Fabric 2: Half Spacer

Test	**Thickness (mm)**
1	3.24
2	3.32
3	3.46
4	3.32
5	3.24
6	3.46
7	3.46
8	3.24
9	3.28
10	3.3
Mean	3.332
S. D.	0.093

Fabric 3: Full Spacer

Test	**Thickness (mm)**
1	6.6
2	6.5
3	6.38
4	6.56
5	6.58
6	6.56
7	6.62
8	6.44
9	6.44
10	6.42
Mean	6.51
S. D.	0.085

Appendix E: Spacer Fabric Thickness Measurement of Pants 2 & 3 After Use

Pant 2*: Half Spacer

Size	Test Area	Thickness (mm)
Small	B1	3.46
	B2	3.28
	B3	3.34
	B4	3.48
	B5	3.28
	L1	3.3
	L2	3.34
	L3	3.28
	L4	3.2
	L5	3.3
	Mean:	3.33
Large	B1	3.24
	B2	3.24
	B3	3.26
	B4	3.34
	B5	3.32
	L1	3.24
	L2	3.36
	L3	3.06
	L4	3.18
	L5	3.32
	Mean:	3.26
	Before Use Mean:	3.332

Pant 3: Full Spacer

Size	Test Area	Thickness (mm)
Small	B1	6.36
	B2	6.3
	B3	6.34
	B4	6.64
	B5	6.56
	L1	6.34
	L2	6.06
	L3	6.24
	L4	6.66
	L5	6.32
	Mean:	6.38
Medium	B1	6.48
	B2	6.72
	B3	6.42
	B4	6.48
	B5	6.48
	L1	6.08
	L2	6.74
	L3	6.66
	L4	6.52
	L5	6.3
	Mean:	6.43
Large	B1	6.5
	B2	6.44
	B3	6.36
	B4	6.56
	B5	6.34
	L1	5.28
	L2	6
	L3	6.04
	L4	5.96
	L5	6.12
	Mean:	6.35
	Before Use Mean:	6.51

*Pant 2 in size Medium was unable to be measured due to test mechanism failure