## ABSTRACT

VEKERT, JENNIFER STAR. Exploring the Dimensional Impact of Pitch Stitches Within Knit Fabric. (Under the direction of Dr. Lisa Parrillo Chapman).

Knitted lace is a structure that uses positive space in the form of knit stitches and negative space in the form of voids to create patterning. Knitted lace can be produced by pitching a stitch sideways along the course and creating a new stitch in the resultant hole. Repeating pitch stitches throughout the fabric produces a lace mesh. Knit lace meshes are used both decoratively, for example to increase translucency, and functionally, for example to increase air permeability. Shifting stitches along the needle bed skews the stitch shape, which then skews the final fabric. The purpose of this thesis is to investigate skewness created by knitted lace structures.

This research consisted of two phases. In Phase One, the scope of skewing in mesh fabrics and possible causes was investigated. In Phase Two, three lace arrangements (Paired, Grid, Staggered) at four percentages of pitch stitches within the fabric (25%, 12.5%, 6.25%, 3.125%) and skewing were examined. Samples were scanned into AutoCAD and the area, perimeter, and angles were measured. The results of the analysis indicate that while arrangement of stitches has no effect on skewness, the percentages of pitched stitches has a significant and predictable impact on skewness. The relationship between the percentage of pitch stitches within the knit fabric sample and the skew of the sample is a polynomial equation.

Exploring the Dimensional Impact of Pitch Stitches Within Knit Fabric

by

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## DEDICATION

*To Aruna*

*For bringing light.*

## BIOGRAPHY

Jennifer Vekert was born in Silver Spring, MD on August 5th, 1989. She learned to weave when she was 7 and to knit when she was 14. She double majored at Earlham College in Studio Art: Hand weaving and Peace and Global Studies. After graduation she ran a hand weaving business until she had a dream about Stargate Atlantis that inspired her to look for graduate programs in textile science. In 2015, she started her Masters of Science in Textiles at North Carolina State University.

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To my wonderful committee.

To Brian, who had to continually help me translate hand knitting to machine knitting terms, occasionally through charades.

To Abbey, my studybuddy soulmate and best pen friend.

To Jules, for making it a judgment free zone.

To Rebecca for lunches and laughter.

To  LSG and PP and all my captial “F” Friends.

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# GLOSSARY OF TERMS

**Consolidation –** When the knitted fabric is off the machine, and the tension required for knitting is no longer being applied, the knitted fabric will relax. During this process the fabric becomes thicker, denser, and slightly smaller. (Kaldor et al., 2008, Knapton & Munden, 1966).

**Course** – A horizontal row of knitting. The term is used in machine knitting. (Spencer, 2001).

**Bending Hysteresis –** bending hysteresis is a quantifiable hand property that incorporates aspects of fabric liveliness and fabric flexibility (Barker et al., 1990; Hollies, 1989).

**Drop stitch fault** – a drop stitch fault will result if a needle releases its old loop without receiving a new one (Spencer, 2001).

**Float stitch** – A float stitch is produced when a needle does not receive the new yarn. The length of unknit yarn can pass in front of or behind the float stitch (Spencer, 2001).

**Hand Knitting** – knitted fabric created by working the yarn by hand into single stitch at a time while the remainder of the live stitches rests on two or more long, cylindrical needles (Krugh, 2014; Rutt, 1987).

**Held loop** – a held loop is an old loop that the needle has retained. It is not released and knocked over until the next, or a later, yarn feed (Spencer, 2001).

**Knit loop stitch** – A knitted loop stitch is produced when a needle receives a new loop and knocks over the old loop that is held from the previous knitting cycle (Spencer, 2001).

**Knock Over** – A phase in the knitting cycle wherein the old loop from the previous knitting cycle is slid off the needle. (Spencer, 2001)

**Lace** – A type of textile patterning created through intentional placement of positive and negative areas within a textile

**Linking** – A means of joining two or more knitted textiles, or to finish an unbound edge of a knitted textile. (Spencer, 2001)

**Links-links** – Alternating courses of front stitch and back stitches. In hand knitting the term is garter stitch and it is formed by knitting every stitch on the right side of knitting and knitting every stitch on the wrong side of knitting when flat, and by alternating rows of knitting and purling when knitting in the round (Spencer, 2001).

**Machine Gauge** – The number of needles per inch on the bed of a knitting machine (Spencer, 2001).

**Machine knitting** – Production of knitted fabric where the yarn is manipulated by machine into one or more stitches at a time and all live stitches are held on an individual needle which may be hooked, barbed, or latched (Krugh, 2014).

**Mesh** – Weft knitted mesh is a type of lace produced by weft knitting machines.

**Pattern** – a repeated combination of stitches (Spencer, 2001; McGregor, 2003).

**Racking** - Racking is a feature of double bed and V-bed flat knitting machines that laterally shifts one bed with reference to the other (Ray, 2012).

**Robbing Back –** Robbing back occurs when a knit stitch in the process of being formed reaches a point in the knit cycle when it is easier to pull yarn length from the previously knitted stitch then to pull yarn length from the yarn carrier. Robbing back occurs with every stitch and certain structures cause more robbing back then others. Very tightly knitted stitches may break, or slide off the needles if they are unable to donate yarn to the robbing stitch. Robbing back is one reason why elastic yarns are preferred for knitting (Gosh & Banjee, 1990; Kane, Patil & Sudhakar, 2007; Spencer, 2001).

**Structure of Knitting** – The structure of knitting refers to the size, shape and interactive forces of an area of knitting or parts of a knitted sample.

**Microstructure** – The fiber properties, fiber arrangement, and yarn structure.

**Mesostructure** – The path the yarn takes in a knit stitch, the shape of a knit stitch, length of yarn in the stitch, and the inter-yarn forces.

**Macrostructure** – Stitch pattern, garment shaping.

**Skew –** Angular displacement of knitted courses from a line perpendicular to the edge or side of the fabric (ASTM D3990-12, 2016).

**Stitch Count** – The number of knit stitches per inch of knitted fabric (Spencer, 2001).

**Course Count** – The number of knit courses per inch of knitted fabric (Spencer, 2001).

**Wale Count** – The number of knit wales per inch of knitted fabric (Spencer, 2001).

**Tuck** – A tuck stitch is produced when a needle holding its loop receives the new loop and the two stitches are not intermeshed. The tuck stitch is therefore two or more loops held on the same needle. Because the held loops are not intermeshed with each other, they do not constrict each other’s shapes. Tucks will therefore spread the fabric horizontally (Spencer, 2001).

**Tuck Presser** – a stocking frame add-on that prevents certain needles from pressing off, forming tuck loops.

**Wale** – A vertical column of knitting. The term is used in machine knitting but not in hand knitting (Spencer, 2001).

**Weft knitting** - A method of machine knitting where yarn feeding and loop formation progress across the needle bed during the knitting cycle (Spencer, 2001).

**Wicking –** the lateral movement of liquid through a textile (Yoo & Barker, 2004).

# 1. INTRODUCTION

Lace is a textile that uses positive and negative space in the form of voids within fabric to create patterning. The English term *lace* is derived from the Latin *laqueus*, which describes, “a hole outlined by a rope, string or thread” (Earnshaw, 1994). There are many ways to create lace. The production method of a particular lace is referred to as the technique (Earnshaw, 1983). Weft knitting is a lace technique that produces simple laces commonly called mesh or, if more ornate, pointelle. This study concerns weft knitted mesh patterns. Hand knitting and hand knit lace are also discussed for contextualization of structure, design and production.

The lace technique discussed in this paper refers to patterns created by utilizing a pitch stitch. Pitch stitches are a type of weft knit stitch that is formed by moving a knit loop one needle to the right through a machine movement referred to as racking. A pitch stitch is composed of two loops knit together that skew in the direction of racking and an empty needle where the pitched loop had previously been located (Shima, 20016; Spencer, 2001). The empty needle creates a void in the fabric that is filled in on the next two rows: on the next row, the needle catches the yarn, and on the third row, a new complete knit loop is formed.

Stitches can be pitched to the right or left. A left pitched stitch and a right pitched stitch possess mirror symmetry to each other and both are distinct structures from a plain knit stitch. Changing a knit stitch to a pitched stitch alters not just the individual stitch but also the inter-stitch interactions that define many of the physical properties of the stitch (Kaldor, James & Marschner, 2008; Yuskel, Kaldor, James & Marschner, 2012). The topic of this paper is the investigation of how mesh structures created from single pitch stitches skew the resultant fabric.

A plain knit fabric forms wales and courses of stitches that sit at right angles to each other (McGregor, 2003). When the wales and courses of a fabric are not at right angles, the fabric is said to be skewed. Pitched stitches do not have the same shape as plain knit stitches and they stack within the wales and courses of stitches differently. Skew is defined by the American Society for Testing and Materials as, “a fabric condition resulting when filling yarns or knitted courses are angularly displaced from a line perpendicular to the edge or side of the fabric” (ASTM D3990-12, 2016). Pitching stitches is known to cause skew but the extent of skew is not predictable.

The knitting industry has produced several technologies that allow shaping during the fabric formation process such as needle bed racking, automatic transfer from needle to needle, automatic transfer from bed to bed, and individual needle control. Shaping during the knitting process can eliminate the need for cutting the knit to shape; significantly reducing the waste incurred in cut and sew knit garment production. In order to knit the final product shape, detailed prediction of finished fabric properties and sizing is needed.

Knitted meshes are created by changing the shape and dimensions of knit stitches in the fabric. Changing the dimensions of the stitches changes the dimensions of the fabric in the course and wale direction (Choi & Lo, 2006). Technologies, such as fully fashioned and integral knitting, where the product shape and dimensions are determined during the fabric formation process, are most affected by the skewing that pitch stitches may cause.

Knitting presents a continuous dialog between the handicraft of knitting and the industry of knitting that informs both designers and consumers (Black, 2002). Analysis of knitting is improved if the dialogue and interrelationship of hand knitting and machine knitting are given due consideration. The terms handicraft and hand-made are historical and social terms, rather than technical ones (Krugh, 2014). For the technical purposes of this paper, *hand knitting* is utilized to refer to knitted fabric created by working a yarn into a single stitch at a time while the remainder of the live stitches rest on two or more long, cylindrical needles. *Machine knitting* refers to the production of knitted fabric where yarn is worked into one or more stitches at a time and all live stitches are held on an individual needle which may be hooked, barbed, or latched (Krugh, 2014).

### 1.1 Objective of Research

The purpose of this research was to study the influence of single pitch stitch mesh structures on skew of knit fabric samples and to develop effective measurement techniques for knit fabric skewness. The following objectives are designed to determine how knit fabric skews with the use of single pitch stitches:

**Research Objective One:** To determine how knit fabric skews with the use of single pitch stitches.

In pursuit of Research Objective One, three sub objectives were identified:

1. To determine the effect of increasing the percentage of single pitch right stitches within a jersey fabric on the skew of a fabric sample.
2. To determine the effect of increasing the percentage of single pitch right stitches within a course of knitting on the skew of fabric sample.

3. To determine the effect of increasing the percentage of single pitched stitches per mesh void on the skew of the fabric sample.

In order to examine the effects of skew on knit fabric samples in a way that was both accurate and relevant to current knit apparel trends, a second research objective was pursued.

**Research Objective Two:** To develop effective methods to measure the skewness of knit fabric samples.

## 1.2 Relevance of Research

Knitted meshes can be found in fashion apparel, athletic wear and athleisure markets. Particularly for athletic wear, the high air permeability of knitted mesh has important applications in thermal regulation. Knitted meshes also have aesthetic functions through the provisions of translucence and surface textures to a knit garment. Knitted mesh's visual association with high performance textiles enables their use as a visual referential to add a sporty and athletic look to athleisure garments. Combined, the performance wear and athleisure markets form the strongest part of the global apparel markets' recent growth (Iredale, 2014; Karr, 2014).

New technologies are available in knitting machine technology that can greatly reduce waste. Reducing waste will improve sustainability of the product but also provides real company benefits in turnaround time, lower costs, and consumer perception (Abbasi, Belhadjali, & Whaley, 2014; Grappi, Romani, & Bagozzi, 2015; Maronde, Stambaugh, Martin & Wilson, 2015). Knitting technologies that enable product shaping during the fabric formation process require a more advanced prediction of knitted fabric sizing and properties.

However, the technology to produce highly accurate simulations does not yet replicate some complex interactions such as the skew caused by mesh stitches or the drawing in of ribbing. Increased understanding of knit fabric size and shaping is required to facilitate the transition to lower waste technologies.

Currently there is no predictive model or digital simulation that can predict the levels of skew. Finishing techniques such as blocking, boarding or steaming are only temporary solutions to skewed fabric because the fabric or garment will return to its structural or skewed state after wear, or after washing. . Skew can only be compensated for through repeated prototyping or through manufacturing through cut-and-sew methods. Findings from this research will contribute to the body of knowledge on shaping during knit formation, that ultimately will help to reduce the number of physical prototypes called for, and facilitate the transition from cut-and-sew production methods to fully-fashioned and integral knitting manufacturing.

It is beyond the scope of this research to provide a detailed predictive model, to observe all possible configurations of knitted mesh, or to modify existing simulation methods. This study established sufficient evidence to suggest that a full predictive model could be possible if a larger study was conducted. For the scope of this study four different percentages of pitch stitches were used, however results suggest that with additional treatment levels a full model could be created using regression analysis and produce reasonable accuracy.

# 2. REVIEW OF LITERATURE

## 2.1 The Structure of Knit Lace

The loop formation process for hand knitting and machine knitting are similar in that a length of yarn is pulled through an existing knit loop to create a new loop that is above the old loop and adjacent to the next loop to be formed. Knitted lace is formed through altering the knitting procedure to produce differences in knit structure that result in patterns of positive and negative space. The basic loop structure of knitting is manipulated through alternative formation methods to create the areas of positive and negative space. Alternative formation methods include repeated tucks, racking stitches after loop formation, adding stitches and subtracting stitches. The alternative formation creates a fabric with a distinct physical structure and therefore distinct physical properties.

Hand knitting and machine knitting are different production techniques for the same fabric or similar fabric. The differences in knit creation processes are more apparent when those processes are adapted to create new structures. The lace produced by hand and the knit meshes produced by machine are very different on the mesostructural level.

### 2.1.1 The Structure of Hand knit Lace

Hand knit lace is created by increasing and decreasing stitches within a row of knitting (McGregor, 2003). In machine knitting, every knit loop must have a corresponding needle, which constrains both stitch count and stitch movement throughout the fabric. Hand knitting does not have that constraint on stitch count. In hand knitting the yarn loops are held on a single needle that threads through the loops, and each loop is knitted in succession. Hand knit lace uses the specific appearance of the different increases and decreases available to create patterning.

The simplest increase is the *yarn over*, abbreviated as YO in many hand knitting pattern instructions. Yarn overs increase one wale and create a void the size of a knit stitch within the fabric. The yarn over is the primary means of forming negative space within hand knit lace patterning. A yarn over is therefore a two-row process: in one row, a void is made through a yarn over and in the second row, the void is filled. [Figure 1]

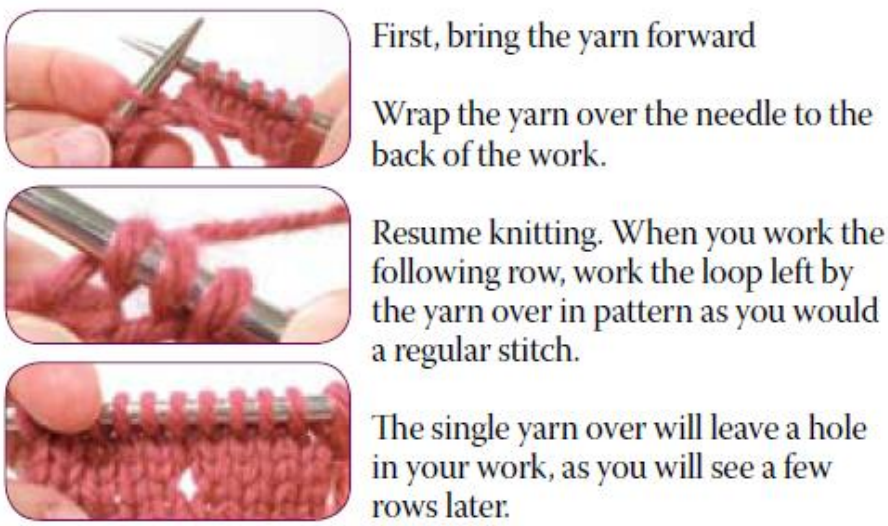


Figure 1. How to form a Yarn Over (Knit Picks, 2009).

The simplest decrease is to *knit two stitches together*, abbreviated knit two together, or k2tog in many texts. [Figure 2] The action is exactly like the name; two stitches are knit together into a single stitch (McGregor, 2003).

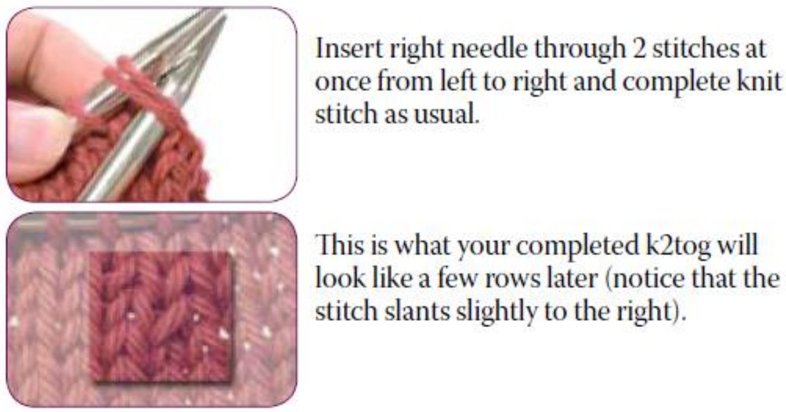


Figure 2. How to form a right leaning decrease (Knit Picks, 2009).

The k2tog stitch leans to the right and decreases two wales into one wale. There are additional decreases, which lean to the left, or that decrease multiple stitches at once. All of the stitches are performed through slightly different actions and have slightly different appearances. To produce a left slanting decrease, known as *slip-slip-knit*, or ssk, two stitches are slipped from the right to the left needle. [Figure 3] While they are on the left needle, they are knit together.

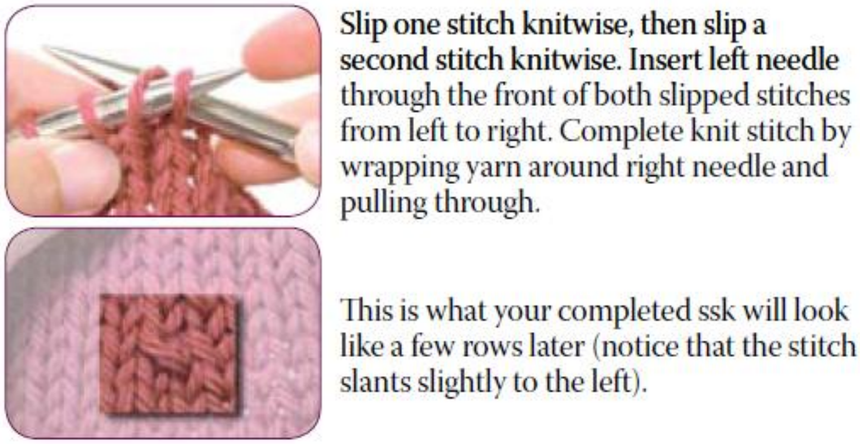


Figure 3. How to form a left leaning decrease (Knit Picks, 2009).

The slip-slip-knit stitch leans to the left much more pronouncedly than the knit-two-together leans to the right. Additionally the slip-slip-knit stitch is much more prominent on the fabric surface, with one leg of the knit loop clearly reaching around two wales. The knit two together stitch displays an entire stitch leaning slightly. The two stitches are highly asymmetric to each other, which is an important factor in hand knit design.

Hand knit lace is created through pairing increases and decreases so that there is no net change in the number of stitches per course. Each decrease in the total stitch count has an equivalent increase in the stitch count elsewhere in the row. The decrease stitches have no requirements to be near the increase stitches that necessitate them. Many traditional lace patterns are created through grouping increases in vertically aligned columns adjacent to vertically aligned columns of decreases. Figure 4 illustrates an alternating pattern of six increases and six decreases repeating across the row of knitting. The vertical dashes represent knit stitches, the horizontal stitches are purl stitches, the circles are yarn overs and the lambda shapes are where two stitches have been knit together. Figure 5 is the actual fabric knitted up. The areas of increases arch upwards and are open. The areas of decreases arch downward and are more compact. The entire knit fabric grid distorts into a wave pattern as stitches move throughout the fabric. Repeated throughout the fabric the aggregate effect is an undulating fabric known as Feather and Fan (Briar, 2016).

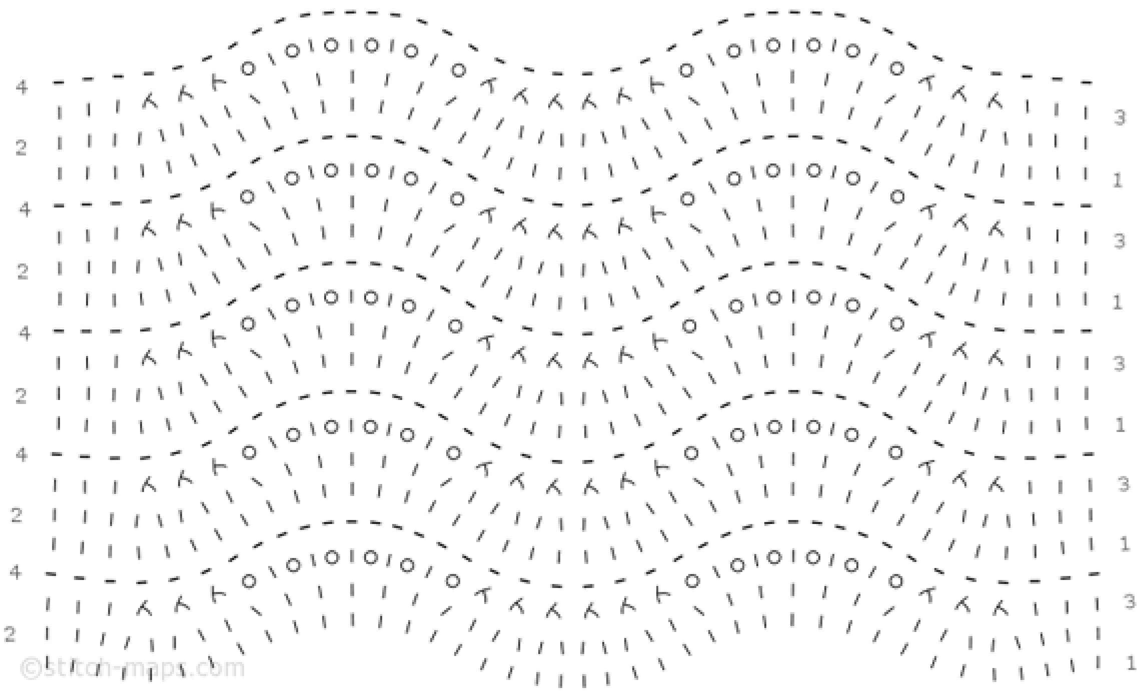


Figure 4. Feather and Fan Stitch Map (Foxyknitter & Briar, 2016).

Figure 5. Feather and Fan stitch (Amadeit, 2013).

The number of stitches in each row can vary considerably. Columns of stitches can be added or removed at any time. [See Figure 6] The rest of the stitches are able to shift relative position on the needles to accommodate the shifting stitch count. The knitting is still grid based; there are still columns and rows of stitches. The curvilinear creations of hand knit lace rely on grouping decreases and increases in separate parts of the fabric.

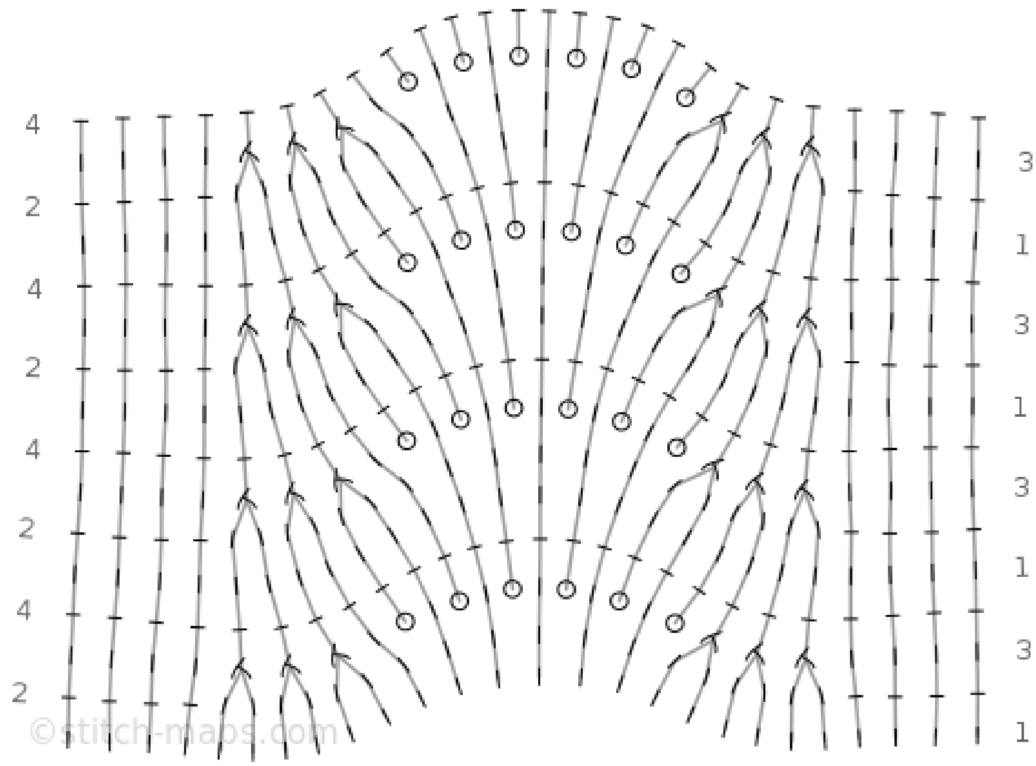


Figure 6. Feather and Fan stitch with Column Guides (Foxyknitter & Briar, 2016).

Patterning is created by varying the increases and the decreases, rearranging them within the fabric, and sometimes even performing both actions in a single group of stitches in a manner more similar to crochet (McGregor, 2003). Estonian and Baltic laces are particularly known for this type of movement, but variations appear in knitted fabrics in Britain and Spain as well. Figure 7 illustrates six different decreases and three increases – the most extreme of which is from two stitches to nine stitches at the base of the flower shapes in the top left of the image. Additionally, the bead-like dense areas of yarn on the border of the bottom right, nupps, are created by making nine stitches into a single stitch and then decreasing those nine stitches back to one stitch in the next row (Johnen, 2009). To produce comparable stitches on a machine, methodologies would need to be developed to create large numbers of stitches from a single starting stitch and also to accommodate the number of needles required to hold each new stitch.

Figure 7. Estonian lace shawl (Knittimo, 2012).

### 2.1.2. The Structure of Machine Knit Lace

In machine knitting there are three types of loops that form the basis of knit fabric: knit, tuck, and float (Ray, 2012; Spencer, 2001). The knit loop is the basic stitch of which fabric is constructed. Tuck loops are formed when the old stitch is not released from the knitting needle after the new loop is formed (Spencer, 2001). They are easily identified on the wrong side of the fabric as an inverted V shape (McGregor, 2003; Rutt, 1987). Float loops are formed when the old loop is not released and no new yarn is added to the needle. The unknit yarn floats behind the stitch (Spencer, 2001).

Tuck loops can be produced in successive courses to create small areas of negative space. [See Figure 8] Lace made in this fashion, especially, tuck presser mesh was very popular for a brief historical moment in the 18$^{th}$ century, but fell completely out of fashion with the decline of lace (Matković, 2010).

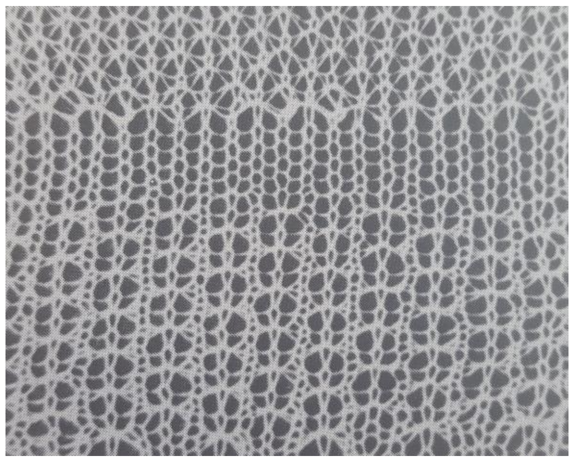

Figure 8. Detail from a Tuck Mesh Sampler (Lorant, 1982).

The lace addressed in this study is made by shifting stitches through a machine movement termed racking. Racking is a term to describe the lateral movement of one needle bed relative to the other knitting bed (Ray, 2012).

A single stitch pitch is created first by knitting the entire course. After knitting, the needle holding the stitch to be pitched transfers the loop to the back bed.  [See Figure 9]

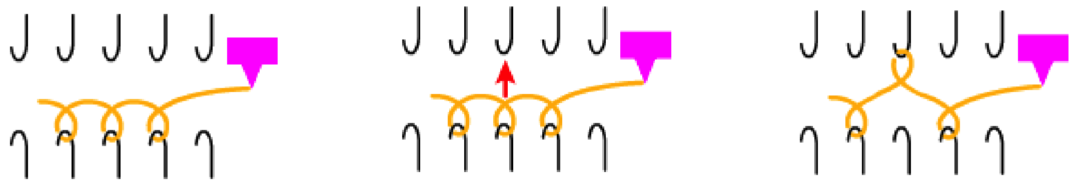

Figure 9. First the course is knitted. Then the stitch to be racked is transferred to the back bed (Shima, 2016).

Racking occurs after the knit loop has been transferred to the back bed. [Figure 10] After racking, the needles transfer the knit loop to the front bed once more. The front bed needle now holds two loops and the original loop location needle has no loops. The beds then rack again to return to the original position.

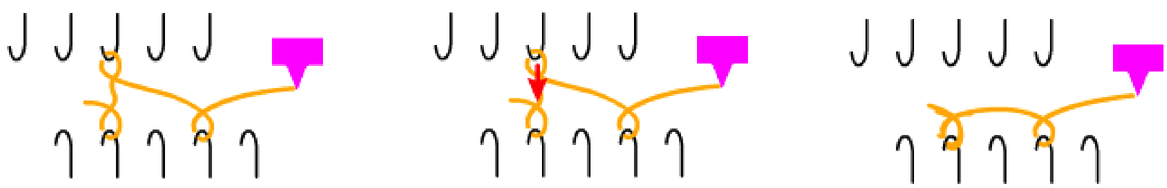

Figure 10. The front and back beds are racked one stitch. Loop is transferred to bed front (Shima, 2016).

When the next row is knit, the empty needle will catch the yarn. The caught yarn acts as a foundation for the complete knit loop on the next row.

Machine knitted mesh is therefore a three-row process. Row one empties the needle, row two places a loop on the needle, and row three knits the loop into a new stitch. The number of wales remains constant (Ray, 2012; Spencer, 2001). Each wale corresponds to a needle in the needle bed and no needles are added or subtracted.

The racking action of the knitting machine is used to pitch stitches within the knitting. Any number of stitches can theoretically be racked any number of spaces. The technical limitation of how far the beds can rack far exceeds the ability of the yarn to stretch. Racking occurs after the loops have been knit and loop length has been set. Racked stitches can rob neighboring stitches of some yarn to complete the difference but the robbing back is limited, especially in patterns where nearby stitches are also racked. Yarn elasticity is therefore a primary limitation on racking. Other limitations include puckering, the increase in machine time, and the resistance of the yarn to abrasion (Ray, 2012; Gosh & Banerjee, 1990; Knapton & Munden, 1966).

#### 2.1.3. Current Market Applications of Mesh Structures.

A key characteristic of lace is that it has negative space where there is no fiber or yarn present. The voids in lace are part of the negative space patterning that creates the delicate transparent aesthetic of the fabric. The voids are also functional in that they increase air permeability. Air permeability in turn is an important criterion for thermal clothing comfort. Comfort in general is hard to define but maintaining thermal balance with the environment is a key component of comfort theory (Barker et al., 1990; Hollies, 1989; Pontrelli, 1990; Prahsarn, Barker, & Gupta, 2005; Rohles, 1971; Woodcock, 1962; Yoo & Barker, 2004). Performance wear is often designed to improve the thermal comfort of athletes during vigorous exercise (Hassan et al., 2012).

Thermal comfort is intrinsically linked to moisture management. Humans produce two types of perspiration. One is the continuous insensible diffusion of moisture between the body and the environment. The second type is the sweat that is produced in reaction to increased thermal strain (Rosenblad-Wallin & Kärrholm, 1987). Humans can produce enough sweat to cool themselves from excess heat strain no matter the activity levels, as long as there is adequate hydration and evaporation (Woodcock, 1962). Impediments for sweat evaporation abound. They include but are not limited to outside temperature, humidity, and clothing barriers. Layers of still air between the skin surface and clothing, or between multiple layers of clothing are a great impedance to evaporation (Woodcock, 1962).

The voids formed by mesh stitches do not transport liquid moisture. Any pore with radius greater than about 350 nanometers will not be able to pull up water through pure capillary action (Prahsarn, Barker & Gupta, 2005; Woodcock, 1962). Capillary action, the passive movement of liquid along a narrow channel, does account for the liquid transported between fibers within knitted fabrics (Prahsarn, Barker & Gupta, 2005; Woodcock, 1962). The voids created by knit mesh are far too large for capillary action to transport liquid moisture.

However, after the liquid has evaporated, knit mesh transports moisture vapor extremely well. The voids of mesh provide very high air permeability. High air permeability is correlated with faster drying times of the microclimate that lies between the skin and the fabric (Prahsarn, Barker & Gupta, 2005). Permeability gives air freedom of movement to form convection currents between the warm skin surface and the cooler air that aid in evaporating sweat off the skin surface.  As air permeability increases, the drying time of the fabric also decreases (Prahsarn, Barker & Gupta, 2005).

Mesh allows air to circulate between the skin surface, the fabric, and the outside environment. The movement of air between the skin and the outside environment allows perspiration to evaporate, cooling the body and preserving a dry hand or feel to the fabric (Prahsarn, Barker & Gupta, 2005; Woodcock, 1962). Mesh is therefore an important structural tool for heat and moisture management.

## 2.2. Historical Overview of Lace and Knitting

Lace and knitting appear in the historical record at about the same time. Machine knitted lace was the first means of mechanically producing lace. Knitted lace was one of the last commercial applications of hand knit lace (Gibson-Roberts, 1985; Rutt, 1987; McGregor, 2003; Levey, 1983).

### 2.2.1. Early Knitting and Lace Making

Evidence of knitting exists intermittently throughout the historical record from about 1100AD on and probably arose in what is now called the Middle East (Gibson-Roberts, 1985). Textile samples do not readily enter the archeological record due to their propensity to decay. Gibson-Roberts, 1985; McGregor, 2003; Pearl-McPhee, 2007; Rutt, 1987). Knitted fabrics are distinguished by their characteristic columns of “v” shaped stitches on the technical face (Compton, 1983; Rutt, 1987). Very similar visual characteristics can be produced through embroidery, sprang and nålbinding [See Figure 11] (Compton, 1983; Rutt, 1987). Figure 11 illustrates how diverse fabrics can be easily mistaken for knitting. On the left is a pair of socks made by sprang, and on the right is a section of nålbinding under construction. Sprang is a type of interlacing of threads into a net which is performed on a loom. (Collingwood, 1974; James, 2012)  Nålbinding, in which short lengths of yarn are looped using an eyed needle, may be the antecedent of knitting. The two fabrics are nearly impossible to distinguish without unraveling samples (Gibson-Roberts, 1985).  Suffice to say simply that knitting is old, but not as old as other fabric making methods such as weaving, felting, and sprang (Collingwood, 1974; Gibson-Roberts, 1985).

Figure 11. Two fabrics easily mistaken for knitting. On Left: Sprang Sock. (James, 2012). On right: Nålbinding under construction (Olavintyär, 2012).

Lace begins to appear in the historical record around the same time as knitting. Levey defines lace as a non-woven fabric and specifies that it can be created either with a single thread on a needle or with many threads on bobbins (Levey, 1983). Levey's definition fails to include the most identifiable characteristic of lace: the creation of patterning through the use of positive space in the form of fabric and negative space in the form of voids. Additionally, Levey’s definition excludes the forms of lace that can be woven such as leno, huck, and Ruskin lace. [Figures 12 -14] Lace is perhaps best defined as a textile characterized by intentional patterning of positive and negative space within a textile, as that is the characteristic that follows the name throughout fabric taxonomies. Earnshaw further simplifies this definition by stating that, “Lace is a lot of holes surrounded with thread” (Earnshaw, 1994, pg. 7).

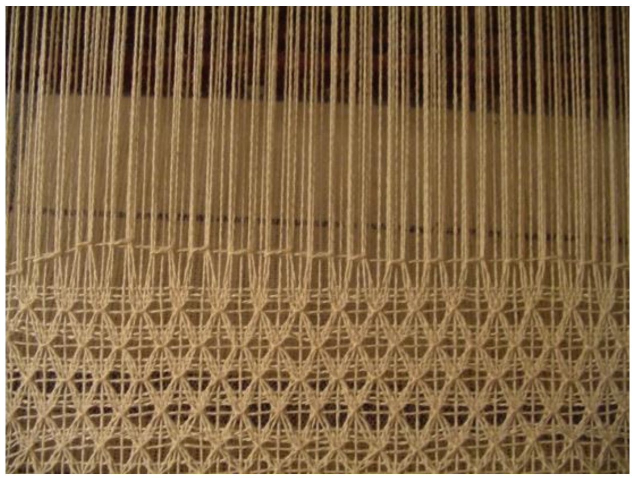

Figure 12. Leno lace in progress on a handloom (Tina 2010).

Figure 13. Handwoven Huck Lace (Weaver, 2010).

Figure 14. Ruskin Lace (Artingstoll, 2010).

Bobbin laces [See Figure 15] began to rise in importance in European dress on the continent starting in the mid-1500s, and by 1600, the manufacturing of lace was well established in England (Levey, 1983). Narrow lace trim decorated woven textiles. Large lace pieces depicted ornate pictorial scenes (Kraatz, 1989). At the same time, knitting machines were being developed. The very first knitting machines were produced in England in the same districts that supported the large cottage lacework industries. The first knitting machine was developed in 1589 by William Lee and it produced stockings (Felkin, 1967).

Figure 15. Bobbin Lace in Progress (Vincent, 2011).

The stocking industry was quite large throughout the 16th century. Stocking frames, as the new knitting machines were called, were engineering marvels. At the time, knitting machines were the most complicated machines in existence with as many as two thousand distinct parts (Levey, 1983). A machine knitter needed both hands and both feet to knit a single row. The end product was a shaped, flat knit pattern piece not unlike modern fully-fashioned knitting. Further developments were able to limit or shorten the required seams for items such as stockings, berets or mittens. As the pace of industrialization increased machine shaping was rejected in favor of higher productivity (Black, 2002).

Machine knitted meshes were first created using tuck loops. Repeated tuck loops creates vertical patterns of negative and positive space. [Figure 8] The formation of tuck loops thickens the positive space in the fabric and widens the fabric, which increases the size of the negative space (Guy, 2001; Kane, Patil, & Sudhakar, 2007; Spencer, 2001). So amazing were the new knitting machines that no less ennobled a figure than Louis XIV is credited with inventing the tuck presser, an addition onto the knitting needle complex which aids in the successful successive placement of tuck stitches. (Levey, 1983).

The openness created by tuck loops was in no way comparable to the great curvilinear landscapes of needle and bobbin laces. However, the fashions in the 1700s were such that rather than laces being centerpieces, they were instead gathered and pleated to soften the brilliantly colored textiles of the day (Kraatz, 1989). Prior to this point sumptuary laws provided strict guidelines for the use of luxury textiles in dress. When these laws were dismantled and revised in the 1700s, lace consumption opened up to the upper middle and middle classes; and there was high demand for the comparatively cheap, open fabric that knitted mesh could provide. The fabric was also often edged with more open needle and bobbin lace (Kraatz, 1989; Matković, 2010).

In the late 1770s there were a number of inventions to improve knitted mesh. By this point weft knitted meshes were competing not just with fine handmade lace but also with warp knit mesh. An innovation by the stocking frame-smith Thomas Taylor allowed stocking frames to create regular hexagonal mesh. [See Figure 16] This fine, sheer mesh could then serve as a base for hand worked lace techniques (Levey, 1983).

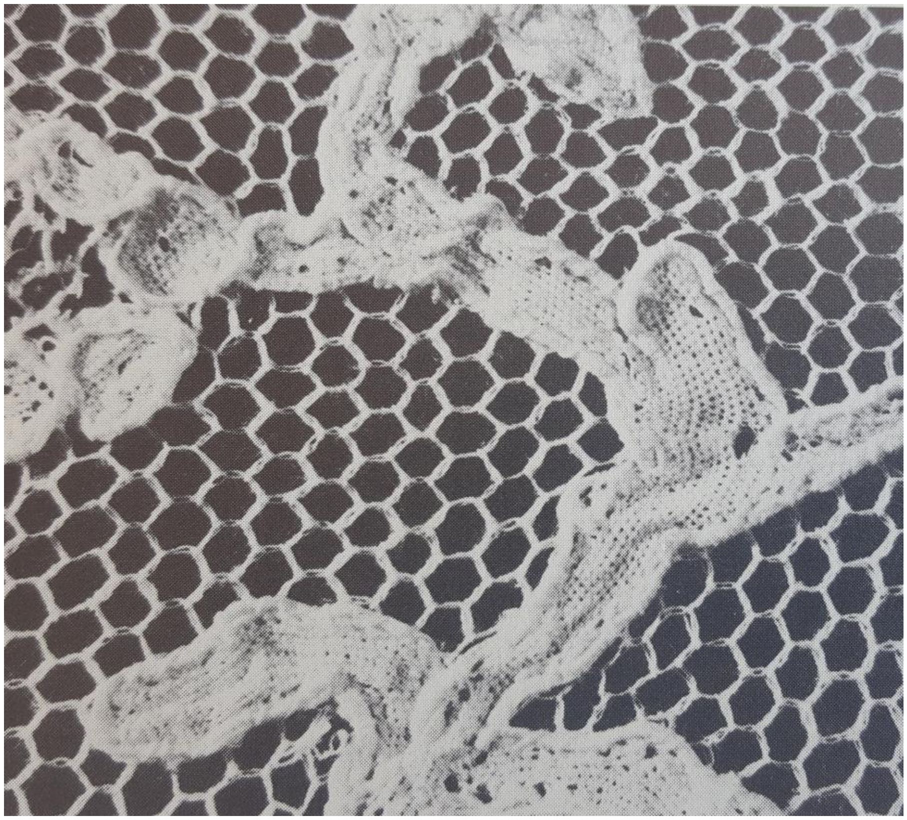

Figure 16. Eighteenth century machine knitted mesh with applique motifs (Levey, 1983, pg. 74).

### 2.2.2. Separation of Lace Making and Knitting

By the latter half of the 1700s knitting and lace were separating. Further developments in knitted mesh to improve durability and shape retention eventually evolved into point net (Levey, 1983). Complex bobbin handling mechanisms allowed greater openness in true machined laces that held more customer appeal then the simple linear knit mesh patterns available (Levey, 1983). Other developments in knitting, such as independently controlled needle selection, made brocade-like patterning available (Matković, 2010). Increasingly the production and use of knit textiles and lace textiles were distinct from each other.

Helping this separation of the two techniques was the abrupt and sudden decline of lace demand. Europe was changing abruptly at this point in time, socially, economically, culturally, and politically. One of the more profound changes was in the performance of gender roles. For centuries in Europe, men consumed more lace than women did. Changes in the aesthetics of gender encouraged men to consume first stiffer, less curvaceous laces, and then no lace at all (Kraatz, 1989).

The collapse of demand nearly killed the burgeoning knitting industry. To make things worse, men started wearing long pants. Suddenly only half the population needed decorative mesh stockings. As hemlines lowered on women, even fewer people sought out decorative socks (Kraatz, 1989; Matković, 2010). Increasingly machines were simpler, and cheaper. Independently controlled needle selection would not be seen again until the invention of the cam in the 20th century, and tuck pressers disappeared completely (Matković, 2010).

**2.2.3 The Resurgence of Lace Knitting as Handicraft**

During the decline of machined lace, hand knit lace began to gain popularity. Hand knit lace was probably always present but it is during this period that major varieties differentiate and begin to gain market share. Shetland in Britain, Faroe in Denmark, and Orenburg in Russia are three of the most notable localities. All are regions with unique wool easily spun into very fine yarns. Through local merchants, they had access to the wealthy classes in cities, and as knitting production outstripped local wool production merchants also provided the raw materials (Gibson-Roberts, 1985; Abrams, 2006). Shawls especially were very popular exports with such notably fashionable ladies as Queen Alexandra of England wearing large lace pieces. [See Figure 17]


Figure 17. Queen Alexandra in a lace shawl (London Stereoscopic & Photographic Company, 1863).

Faroe produced curved shawls [See Figure 18] that stayed securely on working shoulders. Orenburg in Russia [Figure 19] produced garter lace shawls whose plush texture created insulating air pockets (Pearl-McPhee, 2007). Many other locations throughout

Europe also had strong hand knit lace traditions, including the Azores Islands off Portugal, Estonia, Latvia, and all of Scandinavia.

Figure 18. Faroese Shawl demonstrating characteristic shape (Kalessin, 2010).

Figure 19. Orenburg Lace Shawl (Galija, 2015).

Shetland lace is the most studied of all of the lace producing areas of the 1800s. [See Figure 20] The first instance of knitted lace in Shetland was in an 1833 christening cap which had been knit on the mainland and gifted to a Shetland Islander. A female relation of the recipient copied the pattern on the cap and passed it along. The first recorded lace shawl in the islands is recorded a mere six years later, and they appear to be common by 1840 (McGregor, 2003).

Figure 20. Modern reproduction of a Shetland Shawl presented to Queen Alexandra of England (KPiep, 2012).

### 2.3. Knit Production Methods Since the Industrial Revolution

Hand knitting and machine knitting produce knitted fabric through very different production methods. Historically both methods of production generally followed the evolutionary trajectory of making more complex garments with reduced manual labor. Machines have steadily become less labor intensive and able to produce more complex and ornate patterns. Hand knitting production has been steadily removed from the household economy and moved into the realm of leisure and the fiber art world. Machine knitting has primarily progressed through increased centralization. Hand knitting has moved into a more decentralized model of organization.

### 2.3.1 Hand knit Production

Hand knit lace appears in many knitting cultures. Lace is usually knit with wool. However, in the Azores Islands there was no wool, and pita lace shawls were knit with bast fibers from the agave plant (Rutt, 1987). The Shetland Islands do produce very fine wools, but the hand knitting industry used imported yarns from the mainland of Scotland (Abrams, 2006), Fine yarns are certainly a requirement for fine lace. The fineness of the yarn means lace requires small amounts of raw materials — a shawl the size of a twin sized bed might weigh as little as 8 oz. The low input costs and high value added through hundreds of hours of repetitive fine movements mean that lace flourished where there was little capital and an excess of labor (Abrams, 2006; Candee, 2000).

Fine lace aside, hand knitting production provided important additional capacity at times of peak demand. American wars from the Revolution to World War Two were accompanied by campaigns of charity knitting for soldiers (Macdonald, 1988). Donated hand knit socks and other items were primarily distributed through organizations such as the Red Cross Hospitals (Candee, 2000). The knitting was desperately needed — entire new factories needed to be constructed before industrial manufacture could possibly meet the need to outfit armies. Hand knitted items were strictly a donation and the labor strictly an act of patriotism (Candee, 2000; Macdonald, 1988).

Wartime charity knitting drives demonstrate that historically the viability of hand knit production and machine knit production intermeshed. Hand knitting is a very high labor process but it is labor that can be done by children, invalids, elderly etc. who otherwise would not be participating in the workforce; and it is labor that can be done in spare moments between other tasks. During the sudden onset of war, demand for knitted goods exponentially outstripped machine knit capacity. The low input costs of hand knitting were therefore a huge advantage as women or men nationwide could pick up needles and begin knitting.

Hand knitting as a production method has continued to decline but has never quite disappeared. Although a time and skill intensive process, hand knitting does not command a large salary. In 1984, a knitter in England was paid £6 for a sweater that retailed at £200 in a London shop (McGregor, 2003). Eribé Company employs more than 260 hand knitters to produce their hand knit collection line, citing not only the quality and history of hand knitting but also greater versatility of hand knitting to machine knitting (Eribé, 2016). By their own account, one of Eribé hand knit sweaters takes 90 hours to produce (Eribé, 2016). For this reason hand knitting is not usually chosen over machine knitting if machine knitting is capable of producing similar results.

Chronic underpayment for work and poor contract negotiation is an ongoing problem in the hand knitting sector. To combat this, the website whopaysknitters.com provides an anonymous, crowd sourced database of employers who hire freelance knitwear designers, tech editors, sample knitters and teachers. The website details contract information such as whether supplies were provided, perks, licensing details, timeliness of payment, royalty amounts, difficulty of the knitting and personal satisfaction with the contract (Capshaw-Taylor, 2016).

### 2.3.2 Machine Knit Apparel Production

Currently, most knitted consumer items are machine knit rather than hand knit. There are three main strategies for producing machine knit garments: cut and sew, fully fashioned, and integral. The historical movement away from high labor processes that led machine knitting to supplant hand knitting continues to drive developments towards fully automated technologies. An additional pressure driving innovation is the need to reduce waste during knit production.

#### 2.3.2.1 Cut And Sew Knits

Cut and Sew is the most common production method for knit garments. The human labor requirement is quite high and therefore cut and sew factories are primarily located in markets with low labor costs (Peterson et al., 2011). Figure 21 compares the number of steps necessary between different methods of machine knit production. Cut and sew has by far the most steps that require human intervention.

Knitting machines producing fabrics for cut and sew production operations can be circular or flat, based on needlebed orientation. Circular knitting machines can produce large quantities of fabric very quickly due to multiple knitting points along the circular drum (Spencer, 2001). Flat knitting machines produce knit panels from which individual pattern pieces are cut (Peterson et al., 2011). Once the fabric is knit, it is wet finished, steamed flat, cut to size, and then sewn together.

| Cut & Sew |
|---|
| 1. knitting (front, back Body) |
| 2. knitting (sleeves) |
| 3. knitting (trim) |
| 4. cutting fabric to specification |
| 5. manual folding of fabric |
| 6. sewing edges for framing |
| 7. Framing |
| 8. steam setting |
| 9. removing frame |
| 10. cutting fabric to garment spec. |
| 11. overlock of side, shoulder & sleeve |
| 12. bar tacking |
| 13. sewing or linking of neck trim |
| 14. second press |
| 15. attaching label |
| 16. finishing |

| Fully Fashioned |
|---|
| 1. knitting (front Body with NeckTrim) |
| 2. knitting (back body) |
| 3. knitting (sleeves) |
| 4. steam setting |
| 5. sewing |
| 6. linking neck trim or back-body side |
| 7. second press |
| 8. attaching label |
| 9. finishing |

| Integral |
|---|
| 1. knit (front and back body with sleeves) |
| 2. pressing |
| 3. attaching label |
| 4. finishing |

Figure 21. Processes in the three types of industrial knit production (Brackenbury, 1992).

An important aspect of cut and sew construction of garments is that the cutting of fabric to garment size occurs after wet finishing. The majority of dimensional changes occurs during wet finishing of the knitted fabric. Placing the dimensional change before detailed measurements are required allows compensation for change, or to cut around defects by carefully placing the pattern marker. However, while a highly distorted sample may still be able to be cut to the intended dimensions, the seams will be bulkier and may require wider seam allowances (Ray, 2012; Spencer, 1983).

For cut and sew production, material wastage in the form of cutting room loss is a major problem. Raw material costs are the most significant input costs of cut and sew production (Hamilton, 2012). Cutting room loss fabric is fabric that has already been processed, knit and wet finished (Choi & Powell, 2008; Peterson et al., 2011). Cutting room loss is therefore not merely a waste of fabric but a waste of all of the energy, water, chemicals, labor and machine time that went into the formation of the fabric waste.

#### 2.3.2.2. Fully Fashioned Knits

Fully-fashioned, also known as shaped knitting, uses machine shaping to produce shaped panels that do not need to be cut to shape before seaming. Fully-fashioned production is the oldest machine knit production method, as the very first knitting machines were capable of producing shaped panels for socks and hats (Felkin, 1967; Matković, 2010). In fully fashioned knitting fabric waste is reduced to negligible amounts due to the lack of cutting (Peterson et al., 2011).

Fully fashioned knitting has two main constraints. Firstly, seaming knit panels, in particular linking, is a skilled task subject to labor shortages (Parrillo Chapman, 2008). Linking joins two pieces with a chain stitch course for course and creates an unobtrusive, elastic seam. Overlock seaming can cover the raw edges of knitting however, it may also negatively affect quality through bulkiness and difficulty matching stitch density to that of the knitted fabric. Cup seaming also uses a chain stitch but is not course for course and therefore has higher production speed and uses less skilled labor (Brakenbury, 1992; Parillo-Chapman, 2008). Second, in order to shape the garment panels the designer must have a very strong technical understanding of knit and apparel geometry.

#### 2.3.2.3. Integral Knits

Integral knitting removes the need for seaming panels together by knitting a garment in a single piece. Integral knitting is based around the knitting of seamless tubes. To knit a seamless tube, “the yarn only passes across from one needle bed to the other at the two selvage needles at each end thus closing the edges of the tube by joining together the two single-faced fabrics produced on each needle set” (Spencer, 2001).

The minimization of after knitting processes in integral knitting also minimizes the human labor costs. Seaming knit panels together is a highly skilled process and a shortage of qualified workers was a key trigger for the development of integral technology (Parillo-Chapman, 2008). Consequently, integral knitting allows countries with low energy costs and developed infrastructure to compete in the industry despite high labor costs. (Hamilton, 2012) The cost and complexity of machinery needed to knit integrally is the primary disadvantage of this method for knit garment production. The machinery is very complex and takes a higher level of skills from both technician and designer (Choi & Powell, 2008).

### 2.4 Knit Design

The structure of knitting provides knit fabric with unique properties that in turn provide unique design challenges for a designer. Knit fabrics are composed of knit stitches. The mesostructure of knitted loops provide only moderate amounts of inter-yarn friction. The loops can deform and shift around each other (Kaldor et al., 2008; Spencer, 2001; Yuksel et al., 2012).

The elasticity of knitted fabric derives from the knit structure and the mechanics of interlacing loops. The elasticity of knit fabric can therefore only be conceptualized through understanding those structures (Kaldor et al., 2008). Knit fabrics do not behave like simple elastic sheets; they behave in ways unique to knitted materials (Kaldor et al., 2008; Yuskel et al., 2012). Altering the structure of a stitch, changing a knit stitch into a tuck or miss, alters not just the individual stitch but also the inter-stitch interactions that define many of the physical properties of the stitch, and the fabric or garment.

The stitch gauge and garment dimensions are highly influenced by the stitch patterns. [Figure 22] The relationships between structural characteristics of knitting and the visual appearance of a knitted structure are subtle enough to make accurate prediction very difficult (Eckert, 2001). Generally, ribs will draw in the fabric horizontally, cables will lengthen the garment, garter stitch will shorten the fabric vertically, tucks will expand the garment horizontally, etc. (Spencer, 2001).

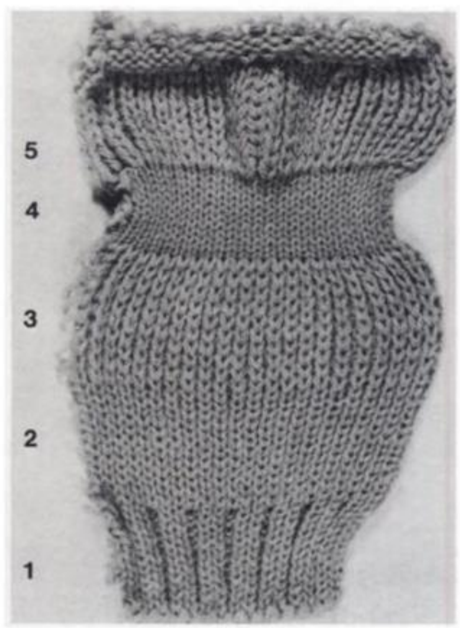


Figure 22. Stitch Shaping. From top to bottom: Full cardigan, tubular courses, half cardigan, 1x1 rib, 2x2 rib (Spencer, 2001).

Eckert describes knitwear design as, “the creation of a technically complex product according to aesthetic considerations” (Eckert, 2001 pg 30). The elasticity and flexibility of knitted fabric structure are positive characteristics of knitted fabric (Ma, 2013). The movement inherent in knit fabrics applies well to, “twisted, inter-looped, or draped effects” in knit garments and presents a fluidity that is not found in woven fabrics (Black, 2002 pg 253). Knit designers need to be more knowledgeable about the technical aspects of their medium than designers in other textile and fashion design mediums (Ma, 2013).

The inseparability of aesthetic design from technical realization is idiosyncratic to knitting and relegates it to a position somewhere between fashion design and textile design (Black, 2002; Eckert, 2001). Designers have to be very knowledgeable about the technical particulars of not only knitted fabrics in general, but also the particular capabilities of their machine and yarn selections. Further complicating matters, there is not a set design methodology that can proceed from start to finish (Eckert, 2001). Every decision made can affect the final garment shape. A designer needs to have sufficient technical knowledge of the behavior of knit stitches to make good initial projections, and then if the design begins to fail, they need to have the knowledge to determine why and adjust their initial parameters accordingly. Each designer must determine their own workflow of cyclical revisions and refinements.

Producing knitted products via cut and sew processes reduces but does not eliminate the technical barriers to good knitwear design. Since the pattern pieces are cut out, a change in the sizing or extensibility of the fabric can be adjusted through changing the cut pattern piece or finishing technique accordingly. Flexibility in fabric dimensions is one of the reasons for the continued popularity of cut and sew despite its high labor costs and high waste production. The movement to fully fashioned and integral knitting has not so much removed the need for skilled labor but shifted it to upfront design time, increased initial design expertise, and increased sampling. Eckert, 2001).

### 2.4.1 Knit Design for Hand knitting

The design complexity of machine knitting is also interesting when contrasted to hand knitting production. There are many fitted hand knit garments that can be knit without any pre-knitting design work at all. Seamless sweaters knit from the neck down towards the hem and socks started at the toe and knitted up towards the ankle are the two most common examples (Walker, 1972). Both start at a place where the number of stitches is very small and very arbitrary - the back of the neck in the sweater example and the tip of the toe in the sock example. From there the garment rapidly increases in size. The knitter simply tries on the garment periodically to determine whether to continue the current aspect of construction or to switch to the next step. Figure 23 shows a toe-up sock being tried on so the calf shaping can be adjusted. The heel shaping will be knit after the top has been cast off (Walker, 1972). The finished garments are customized, generally seamless, and require only light finishing. They are most similar to integral knitting in construction despite having a process most dissimilar to integral knitting.

Figure 23. Sock in progress being tried on (Walla, 2015).

#### 2.4.1.1. The dialogue between Hand knit Design and Machine Knit Design.

Very few industrial material sciences maintain ties of any sort with their craft heritage (Black, 2002). Knitting is in a continual dialogue between the hand knitting community and commercial knitwear and often machine trends try to emulate the “cozy familiarity of hand knitting” (Black, 2002, pg. 258).

Hand knitting trends have also driven machine knitting innovation. During the 1980s when computer technology was just integrating into industrial design applications, hand knitting was popularizing complex and vibrant patterning (Black, 2002; Matković, 2010). Hand knitting icons like Kafe Fasset and Alice Starmore brought into fashion boldly patterned sweaters with many colors. The popularity of complex patterns put pressure on machine producers. In order to replicate the hugely popular patterns, machine producers had to add more yarn carriers and improve yarn-handling capabilities while maintaining quality, manufacturability and cost controls. (Matković, 2010).

By the 90s, intarsia technology had improved to the point where 24 or even 32 yarns could be included in a pattern (Schenk, 2005). To go with this exponential increase in patterning, the first digital design systems were produced to go along with the machines. For example, Steiger, the maker of Aries machines, paired their new machines with the garment design software Lectra (Schenk, 2005). By incorporating their own in house software with the established Lectra Systems, they created knit specific software that allowed designers to adapt patterns and gauge to stitch structures (Schenk, 2005).

Hand knitting exerted pressure on designers as well as machine manufacturers. Hand knitting design falls into the category of whole garment engineered designing; that is, the knit structure is strategically placed within and purposely for the shape of the end product (Parrillo Chapman, 2008). The result is a very different aesthetic than when a large fabric, no matter how intricately patterned, is cut up and sewn together. The hand knitting trend educated and informed consumer preference for machine knit products (Matković, 2010).

### 2.4.2. Computer Aided Design for Knit Garment Design

The proliferation of computer-aided design for knits is an attempt to address the complexity of knit design. CAD systems provide a “virtual design space where the designer can test out ideas,” without having to physically produce samples (Erskine, 2012, pg. 25). They also provide a common language to, “convey a new concept to fellow designers, technicians, and all others who help to create the final product” (Erskine, 2012, pg. 25).

Previously knit textile design and apparel silhouette design had been two separate tasks by people with separate skills and education. Computer Aided Design systems conjoined these tasks under a single designer who could treat knits as knits, not just as a generic extensible fabric (Erskine, 2012).

### 2.4.2.1. Knitted Fabric Geometry and Modeling

Simulation provides one of the key advantages of CAD systems. Knitting does not have an analog material that can create an informative mockup the way clay can mock up a bronze casting or balsa wood can mock up a building. Digital simulation of knit fabric provides a means of prototyping a knit product short of actually knitting it.

Digital simulation of knit products is dependent upon knitting models. Models should have only the details necessary for representation. It has been established in textiles that everything from microscopic fiber structure to fiber arrangement within yarn, yarn twist, loop formation etc. all have an effect on the finished garment. Choosing which details to include in the simulation depends on processing capability, data availability, and purpose of the finished model (Beil & Roberts, 2002a; Beil & Roberts, 2002b; Kaldor et al., 2008; Lin et al., 2012; Zhang et al., 2012).

Early knit models began with the assumption that, "plain-knitted fabric is made of frictionless, inextensible, incompressible, and naturally straight yarn and is subjected to uniformly distributed loads along its edges" (Hepworth & Hepworth, 1975, pg. 86). This set of characteristics does not particularly describe actual knitted fabric. Simplifying knit structures in this way allowed for the definition of the interactions between loops, especially in "the interlacing region and at possible course-and wale-jamming points" (Hepworth &

Leaf, 1976, pg. 7). Subsequent models have clarified those assumptions to create a more naturalistic model, including considerations of the geometric nature of yarn and how yarns interconnect within the loop structure (Nutting,1970).

Digital simulation of knits is also relevant to the advances or developments in the video game industry. Ever increasing graphics requirements for games necessitates more detailed costume and set design in digital environments. Woven garments are generally simulated through, “models that approximate the mechanics of linear elastic sheets” (Kaldor et al., 2008, p. 1). When these models are adapted to the elasticity values of knit garments, the simulations lose verisimilitude and appear rubbery (Kaldor et al., 2008). The difference in appearance, “is unsurprising, since the mechanics of interlocking loops in a knit fabric bears little resemblance to the mechanics of a continuous elastic material” (Kaldor et al., 2008, pg. 1).

The models used in the gaming industry prioritize accurate appearance and behavior for coarsely knit garments for characters (Yuksel et al., 2012). Gaming models produce animated simulations that stretch, bunch, and flow realistically by focusing on the mesostructure of yarn-to-yarn interactions including yarn kinematics, intra-yarn forces, and inter-yarn forces (Yuksel et al., 2012; Zhang et al., 2012). Gaming models focus precisely on the aspects of knitting which many knitting industry methods deemphasize or ignore. Figure 24 illustrates the visual realism that virtual simulation through gaming models achieves. The simulation depicts the stitch deformation that characterized the patterning in Figures 4, 5 and 6. Gaming models are scaled for coarse hand knitting, with samples of less than 5,000 total stitches producing, “over 100 billion pairs of quadrative points that potentially need to be evaluated for the collision integral at each step," in a process that takes over ten minutes for a single image (Kaldor et al., 2008). Full garment simulations at common machine gauges would have exponentially more stitches and therefore calculations to make.

Figure 24. Virtual Simulation of a sheep wearing a sweater (Yuksel et al., 2012).

The ultimate goal of simulation for the knitting industry is to eliminate the need for physical prototyping (Choi & Powell, 2005; Erskine, 2012). Gaming models may be unwieldy for simulating for industrial knit design. Currently, it would be faster to knit a prototype. Gaming models are capable of accommodating yarn level relaxation after knitting and knit structure-derived elasticity (Yuksel et al, 2012). The current industrial models rely on user knowledge to estimate many of the consequences of yarn-to-yarn interactions. An ideal system would not rely on implicit knowledge.

A true digital prototyping solution should be able to show not only how a garment fits but if and how it needs to be altered (Erskine, 2012). Current models are approaching but have not reached Erskine's standard. Physical testing is still needed to observe fabric phenomena excluded from digital knitted fabric models.

### 2.5 Conclusion

In conclusion, knitted fabric is a geometrically complex fabric that has been insufficiently modeled which leads to technical difficulties throughout the process of conceptualization, design, and manufacture. In an attempt to further elucidate the geometry of knitted fabric, this thesis proceeds to examine how the presence of single pitch stitches changes the skewness of the fabric. Thusly this research will contribute to better prediction of knit fabric geometry and reduce the necessity of repeated sampling.

# 3. METHODOLOGY

## 3.1. Introduction

In order to determine the effects of pitched stitches on fabric skew, this research consisted of two phases. In the preliminary phase, an exploratory investigation was conducted to understand the scope of skewing in machine knit mesh fabrics. Based on information gleaned from the preliminary investigations and search of prior research within the review of literature, a design of experiments was developed for the second phase that sought to test three factors identified as possibly influencing skew. The experiments compared the shape distortion of samples containing varying amounts of single pitch right stitches arranged in either grid, paired, or staggered arrangements.

The preliminary research phase component of the research features two attempts to translate hand knittingpatterns into machine knitting files. A dress featuring two leaf mesh patterns taken from Shetland lace and a sweater featuring a variant of the lace rib pattern were designed and knit on a Shima Seiki Mach 2X 8 gauge knitting machine. Both garments had significant skew of mesh areas altering the overall shape and fit. In the case of the sweater, this was successfully corrected by altering the knit pattern file to include equal numbers of left and right racked stitches.

Three factors were identified during the preliminary phase that could influence skew and these were investigated in the experimental phase. The first factor tested was the number of pitched stitches in ratio to the number of un-pitched stitches. To test this factor, all three arrangements of stitches were examined separately to record how the percentage of pitched stitches within the fabric sample influenced skewness within each population. The second factor tested was the number of stitches pitched in each course of knitting. To test this factor, skewness of the grid arrangement was compared to the skewness of the staggered arrangement, which has half as many pitched stitches per course, at each level of pitched stitch percentage. The third factor tested was the number of stitches pitched compared to the number of voids formed by pitched stitches. To test this factor, skewness of the grid arrangement was compared to the skewness of the paired arrangement, which has half the number of voids per pitched stitch, at each level of pitched stitch percentage. A design of experiments was developed that tested each of the three arrangements and tested them separately in three experiments.

The variable of interest in all three experiments is the angle of intersection between courses and wales, specifically how much it differs from 90º (Spencer, 2001). Previous studies on fabric shape first involved aligning courses and wales to 90º before measurement (Ruan, 2011). A new method of measuring fabric sample shape was created suitable for the analysis of fabric skew.

### 3.2 Preliminary Research

Preliminary research began with translating several hand knitting stitch structures into machine code. The patterns were combined into a dress design and knit on a Shima Seiki Mach 2x.

The bodice of the dress was a leaf lace pattern drawn from Shetland knitted lace as seen in Figure 25. Translation from hand knit structures to machine knit structures was determined to be sufficient for the integrity of the design due to visual structure comparability and the integrity of the aesthetic design. Hand knit decreases and increases were replaced with rows of racking to create stitches leaning in the correct formation to produce a leaf-like visual effect.

Figure 25. Leaf lace motifs. Left: hand knit inspiration (addknitter, 2009). Right: machine knit facsimile.

The skirt of the dress was filled with a simple mesh structure and larger versions of the Leaf Lace motif. The mesh pattern was created with single right racking stitch filling the space around the large leaf motifs.  The dress was knit on a Shima Seiki 8 gauge Mach2x machine. The yarn was Glassa, a 6.5 Nm 75% cotton and 25% polyester wrapped yarn. The loop length throughout the bodice and the skirt of the dress was 10.

When the dress was knit, the left side of the dress (right side of the Figure 26) was longer than the right.

Figure 26 Knit dress with uneven hem lengths.

Machine tension and yarn tension were eliminated as factors in the skewing after consultation with the machine technicians. Analysis of the top of the garment revealed no skewing or deformation. A machine or yarn tension fault would have also affected the top of the dress. The cause of the skewing was determined to be the knit structure of the skirt. The floral dress was unable to be simulated due to the neck design option. Simulation of just the skirt showed no skew.

A second garment was made in the preliminary phase, this time translating a very simple Lace Rib hand knitting pattern into machine knitting. Several variations of Lace Rib were used to shape a loose tunic sweater. The yarn was 100% cotton ringspun 16/2 knit double. The loop length throughout the body of the sweater was 10.5

The garment was knit twice. The first time there was significant skewing to the left of the technical face of the garment as seen on the knitting machine. [Figures 27, 28] Machine tension and yarn tension were again eliminated as factors due to inconsistency in presentation through the knitted length of garment. Areas of the garment without the mesh rib pattern had no skew and tension was consistent throughout the garment.

Figure 27. First knitting of the green sweater. Knit Garment on the left. Simulation on the Right.

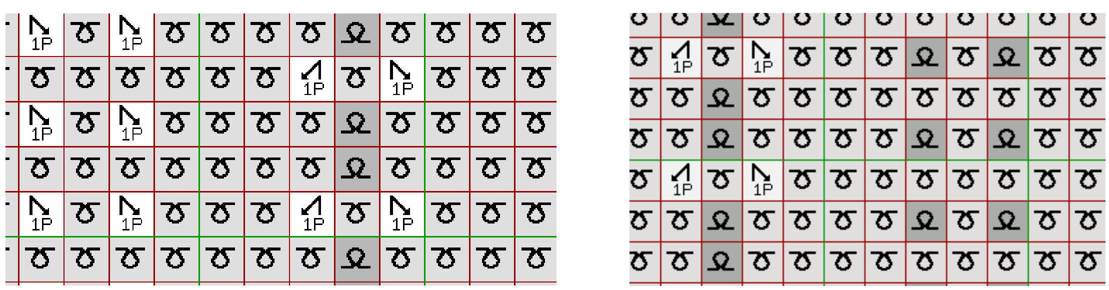

Figure 28. Two Versions of Mesh Rib. Chart created with SDS-ONE APEX.

Other problems were identified concerning the aesthetic flow of the multiple mesh patterns that did have clear solutions. The multiplicity of mesh patterns had been intended to create varying fabric widths. The garment dimensions indicated that the different mesh patterns had no effect on fabric width. The patterns were also intended to flow smoothly from one to the other. The transitions between patterns were abrupt and obvious. For example in Figure 27 the vertical lines of ribbing along the waist of the sweater change to diagonal lines in the peplum. This increased the visual complexity and created a less refined texture than desired.

The mesh patterns were simplified to a single mesh pattern with a smoother texture and the garment was reknit, with the intention that the skew could then be isolated and corrected. [Figures 29, 30] The second knitting of the pattern showed no skew.

Figure 29. Second knitting of green sweater. Knit sweater on the left. Simulation created with SDS-ONE APEX. on the right.

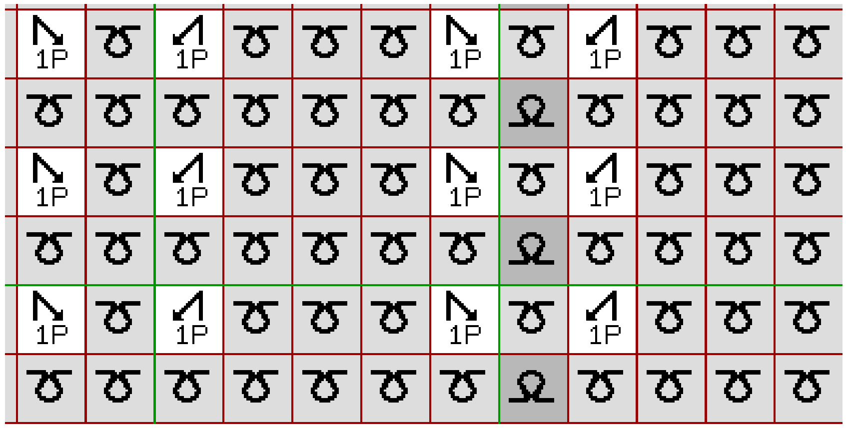

Figure 30. Second Version of Mesh Rib. Chart created with SDS-ONE APEX.

Closer examination of the Mesh Rib versions used in both sweaters revealed that when changing the pattern between iterations, the second iteration to knit had a balanced amount of left pitching stitches and right pitching stitches. The mesh rib versions used in the first iteration had unequal amounts of left pitching stitches and right pitching stitches. [See Figures 28, 30]

The change to the mesh rib had been undertaken to smooth visual appearance and to simplify the number of pattern versions used. Balancing the number of left and right pitch stitches was the coincidental effect of design simplification. The transition between several mesh rib patterns had been unsatisfactory, and all patterns had been replaced with a single mesh rib pattern. When the second sweater was examined for possible causes of the reduction in skew, it was the symmetry of the pattern that seemed a likely cause. The leaf lace bodice of the dress was symmetrical in how it pitched stitches to the left and right. The bottom of the leaf lace dress has far more right pitches then left stitches. The balanced patterns did not skew. The unbalanced patterns did.  This was unexpected because hand knitting left and right leaning stitches are very different and not symmetrical.

### 3.3. Experimental Phase

Findings from preliminary research suggested that pitch in knitting stitches could cause skew, and that equal numbers of left pitch stitches and right pitch stitches would show no skew. The results of phase one indicated a need for increased depth of study on the phenomena of unbalanced pitch stitches and skew.

#### 3.3.1. Sub Objectives

The first Objective of this research is to determine how knit fabric skews with the presence of single pitch right stitches. The single pitch stitch is the simplest type of pitch stitch. The single pitch stitch moves a single needle to the right without back knit or kickback. Isolating the racking movement ensures that the pitch is isolated as a variable. Single pitch stitches can rack to either the left or the right. In contrast to hand knitting, where left and right leaning stitches have different formation and structure, the machine movement that creates the left and right leaning pitch stitches differs only in direction (McGregor, 2003; Spencer, 1983). To examine Objective One, three Sub Objectives were developed.

> Sub Objective One: To determine the effect of increasing the percentage of single pitch right stitches within a jersey fabric on the skew of a fabric sample.

> Sub Objective Two: To determine the effect of doubling the number of single pitch right stitches within a course of knitting on the skew of the fabric sample.

Sub Objective Three: To determine the effect of halving the percentage of single pitched stitches per mesh void on the skew of the fabric sample.

### 3.3.2. Experimental Design.

Every experimental stitch arrangement was knit five times. For Sub Objective One of Objective One, five copies of each of the four pitch grid arranged stitch percentages were knit. For Sub Objective Two, five copies of each of the four staggered arranged stitch percentages were knit and then compared to the grid arranged stitches from Sub Objective One. For Sub Objective three, five copies of each of the four paired arranged stitch percentages were knit and then compared to the grid arranged stitches from Sub Objective One.

For Objective One, each of the five replications had four corners that were measured for a total of twenty replications of each experimental condition. For Objective Two, the same samples from Objective One were used. Objective Two examines area measures rather then corner angles, so five measures were taken for each experimental condition. In Objective Two five control samples with no pitch stitches were knitted.

Experimental stitch arrangements were created as a pattern square with dimensions sixteen stitches by sixteen stitches for a total of 256 stitches. The 16x16 pattern squares was repeated forty-two times to create to create experimental fabric samples of a single pattern structure. Samples were knitted on a Shima Seiki SRY 123lp 14 gauge knitting machine set for a loop length of 8.5. The yarn used was a wool yarn chemically treated for machine washability with a size of 2/24 and an S-twist at 14 turns per inch.

Sub Objective One was examined by comparing fabric samples with decreasing percentages of single pitch right stitches. Pitching a stitch causes it to lean to one side, to be denser, and to apply more tension to its neighboring stitches then a plain knit stitch (Knapton & Munden, 1966; Ray, 2012). If increasing the number of single pitch right stitches within the fabric sample increases the skew, then it would indicate the shape of the pitched stitch changes the shape of the fabric sample.

The range of knit stitch percentages was created through halving each successive percentage of pitch stitches. The number of single pitch right stitches began at the 25% pattern square having 192 jersey knit and 64 single pitch right stitches [See Figure 31], the 12.5% patterns were 224 jersey knit stitches and 32 single pitch right stitches [See Figure 32], the 6.25% had 240 jersey knit stitches and 16 single pitch right [See Figure 33], and the 3.125% patterns had 248 jersey knit stitches and 8 single pitch right stitches. [See Figures 34]

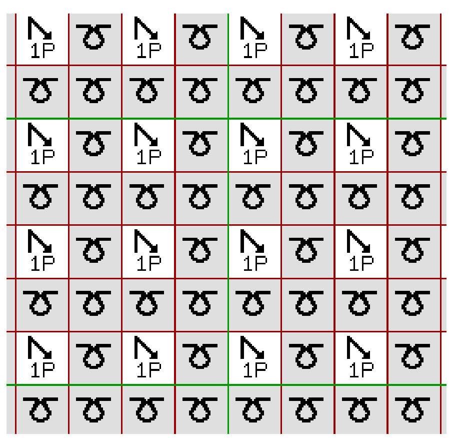

Figure 31. Grid Arrangements at 25% Chart created with SDS-ONE APEX.

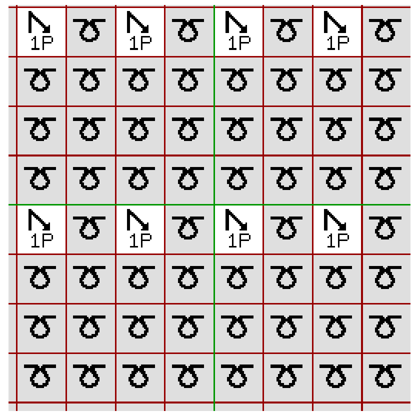

Figure 32. Grid Arrangement at 12.5% Chart created with SDS-ONE APEX.

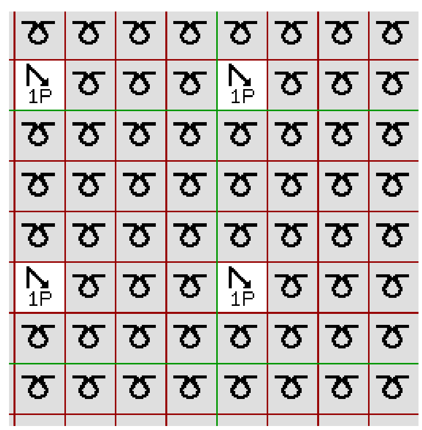

Figure 33. Grid Arrangement at 6.25% Chart created with SDS-ONE APEX.

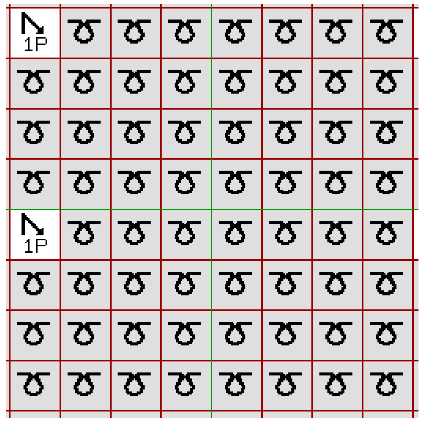

Figure 34. Grid Arrangement at 3.125% Chart created with SDS-ONE APEX.

Sub Objective Two was examined by comparing fabric samples with single pitch right stitches either arranged along a grid or staggered. Staggering the pitch stitches halved the number of pitch stitches within a single course without changing the total ratio of pitched stitches to knit stitches. [See Figures 35, 36] Staggered stitch arrangements are therefore more evenly dispersed among the jersey fabrics. Staggered arrangements were made at pitched stitch percentages of 25%, 12.5%, 6.25% and 3.125%. The staggered arrangements were compared to the grid arrangements from Sub Objective One. Two arrangements at each of four densities equals eight experimental conditions. If increasing the number of single pitch right stitches per course of knitting increased the skew, then it would indicate that concentrating the pitched stitches within specific courses increased the total amount of skew in the fabric. In this scenario, single pitched stitches in proximity to each other have an additive effect on the amount of skew each stitch produces.

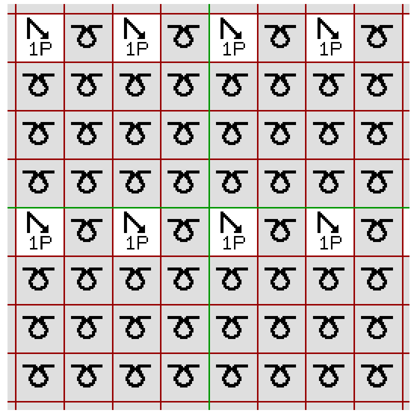

Figure 35. Grid Arrangement at 12.5% Chart created with SDS-ONE APEX.

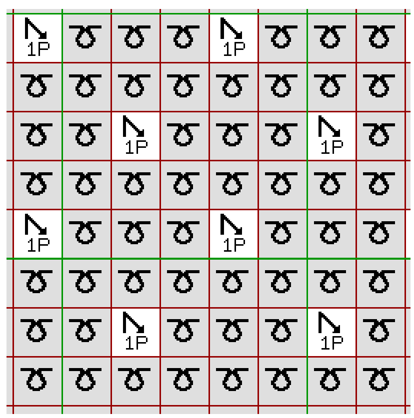

Figure 36. Staggered arrangement at 12.5% Chart created with SDS-ONE APEX.

Sub Objective Three was examined by comparing fabric samples with pairs of adjacent pitch stitches to samples with the same number of total pitch stitches arranged singly. [Figures 37, 38] Two arrangements at each of four densities equals eight experimental conditions. The pitched stitch has two distinct parts, the stitches that are leaning and the mesh void. When pitched stitches are adjacent to each other they are moved as a unit and a single mesh void is formed. Pairing stitches adjacently halves the number of voids per leaning stitch. The mesh void compensates for the movement of the pitched stitches out of alignment. If the formation of the mesh void has a limiting effect on fabric distortion then a paired arrangement of stitches will show less skew then an unpaired arrangement.

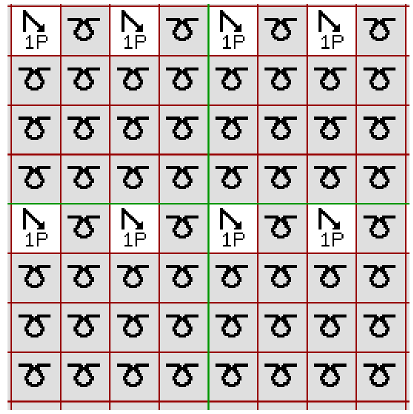

Figure 37. Grid arrangement at 12.5% Chart created with SDS-ONE APEX.

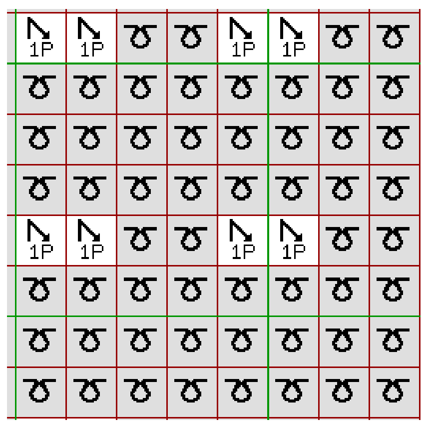

Figure 38. Paired arrangement at 12.5% Chart created with SDS-ONE APEX.

### 3.3.3. Knitting Procedure

The experimental fabric samples were arranged vertically in three groups for knitting sequentially. Knitting in strips reduced the number of times it was necessary to cast on and cast off so that time on the machine was minimized. The cast on and cast off process of knitting are comparatively slow to complete. The knitted strips were organized by stitch arrangement, with one strip knitting the paired set, one strip knitting the grid set, and one strip knitting the staggered set.

Between each sample pattern, there were five rows of jersey knitting. This was to assist in separating the patterns. A border pattern balanced between front stitches and back stitches would help the knitting lay flat or prevent rolling. Research conducted by Ruan demonstrates that changing or introducing border stitches has very little influences of overall dimensions along the armscye of sweaters. The reason proposed in the research was the sheer numbers; there are not very many border stitches in Ruan's sweater samples and there are a large number of body stitches in the sweater samples (Ruan, 2011).

In addition to the experimental pattern squares, five pattern squares were knit that had no pitch stitches. This sample set served as a control and was used in establishing the method of measuring the samples. (Research Objective Two).

The experimental fabric samples were bordered on all four edges by six stitches of links-links pattern. Experimental fabric samples were bordered in links-links pattern to prevent edge curling. Plain knitted fabric has a pronounced spirality and tendency to curl along the edges. The outer wales of a rectangular swatch will curl inwards towards the technical back. Likewise, the outer courses of the same swatch will curl towards the technical face of the fabric  (Choi & Lo, 2006; Kaldor et al., 2008; Ruan, 2011; Yuksel et al., 2012).

The meeting of two stitch patterns within a knit sample can cause distortion such as arcing or bowing the fabric. Tou explored this phenomenon and found that fabrics knit at medium tightness experienced fewer distortions and that the most arcing occurred when there was a large difference in structural stability between the two structures (Tou, 2011).

It was, therefore, decided that a narrow border of links-links would be placed along the border of all of the samples. At six stitches along each side, it is enough to prevent curling edges while still being only 11% of the stitches per row.

A links-links stitch was chosen for two reasons. Firstly, it does not pull in horizontally the way many ribbed fabrics do. Secondly, links-links stitch shows the backstitch of the fabric raised above the jersey background. It is therefore very easy to determine visually the borderline between links-links stitch and the test samples in the scanning process. An additional benefit is that knitting errors tend to cluster along the edges of fabric. In several of the knitted samples, there were yarn breakages in the links-links edge that did not extend into the test fabric allowing those samples to be included. [See Figure 39]

Figure 39. Example of Edge Flaw.

An example of the final sample strip is in Figure 40. Samples were knitted on a Shima Seiki SRY 123lp 14 gauge knitting machine. The loop length was set at 8.5. The Shima Seiki SRY 123lp is a computerized flat knitting machine designed to handle diverse yarns in diverse knit structures. Each strip was knitted five times.

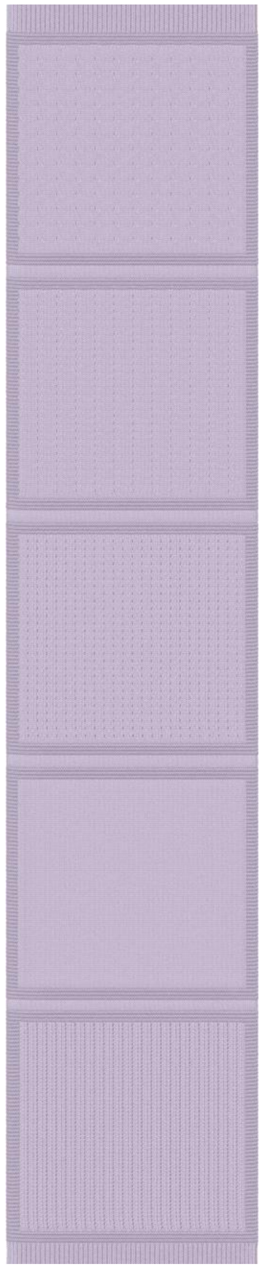

Figure 40.  Simulation of grid sample strip. Simulation created with SDS-ONE APEX.

#### 3.3.3.1. Yarn

Yarn was provided by Ductworth Company of Bozeman, Montana, USA. The yarn was 2/24 Rambouillet wool grown and processed within the United States. The yarn is an S twist with 14 turns per inch.

Wool was selected for good extensibility that allowed loop transfer with minimal errors. Additionally, there has been an increase of wools in the market for active wear (Sneddon, Lee & Soutar, 2012a; Sneddon, Lee & Soutar, 2012b). Mesh or open work structures are used for perspiration management within active wear. Wool has also been traditionally used for the finest hand knit laces (Pearl-McPhee, 2007; Rutt, 1987).

Rambouillet is a French breed of sheep derived from Spanish stock gifted to France and then exported to Germany and the United States. Rambouillet sheep are the largest of the finewool breeds and Rambouillet wool has very fine, even crimp with a staple length of 5-10 centimeters and fineness of 19-23 microns (Parkes, 2009).

### 3.3.4. Sample Finishing

Finishing is an important part of knitting production. Yarn is stretched under a lot of force during knitting and then the fabric is pulled down sharply by the comb and rollers (Knapton, et al., 1968).

After knitting the samples were dry relaxed for 24 hours in 24ºC. Consolidation decreases loop length, which is a primary parameter for determining knitted fabric properties (Duru, Candan, & Mugan, 2015; Higgins, Anand, Hall, & Holmes, 2003; Kane et al., 2007; Knapton et al., 1968).

Ductworth Company gives the following washing instructions for its products: “hand-wash or gentle/wool cycle warm. Mild detergent. Hang dry or dry flat. Do not tumble dry” (Ductworth, 2016). Additionally, AATCC TM 179 Skewness Change in Fabric and Garment Twist Resulting from Automatic Home Laundering provides a detailed set of Alternative Washing and Drying Conditions to be adapted to different fabric types and usage scenarios. [Figure 41]

**Table I—Alternative Washing and Drying Conditions**

| Machine Cycle | Washing Temperatures | Drying Procedures |
|---|---|---|
| (1) Normal/Cotton Sturdy | (II) 27 ± 3°C (80 ± 5°F) | (A) Tumble: |
| (2) Delicate | (III) 41 ± 3°C (105 ± 5°F) | i. Cotton Sturdy |
| (3) Permanent Press | (IV) 49 ± 3°C (120 ± 5°F) | ii. Delicate |
| | (V) 60 ± 3°C (140 ± 5°F) | iii. Permanent Press |
| | | (B) Line |
| | | (C) Drip |
| | | (D) Screen |

Figure 41. AATCC TM 179 Skewness Change in Fabric and Garment Twist Resulting from Automatic Home Laundering Table I

The samples were washed in the NCSU Pilot Lab home washing facilities using a GE Whirlpool machine on the Wool cycle, which specifies low soil level, low spin speed, and unheated water. The detergent used was high efficiency commercial laundry detergent provided by the Pilot Lab for home laundering testing.

The GE Whirlpool Wool cycle is in accordance with Ductworth Co.’s washing instructions and an approximation of AATCC TM 179 Alternative Washing and Drying Conditions. Notably, the unheated water was 10-20ºC colder than the coldest temperature recommended by AATCC and no ballast was added to balance the load. Both of these adjustments were chosen to reduce the possibility of felting of the samples. Partial felting could limit the ability of yarns to move and skew. Reducing the heat and friction on the yarns reduced the potential for felting without varying from Ductworth's instructions. Additionally, research has emphasized the importance of thorough wetting over temperature in the wet finishing of fabric (Higgins et al., 2003; Knapton et al., 1968; Nutting, 1970).

The samples were dried for 24 hours in 24ºC still air against a 100% polyester screen, in accordance to both Ductworth Co and AATCC TM 179 Alternative Washing and Drying Conditions Drying Procedure D.  The samples were gently laid flat with minimal manipulation, pinning or boarding. The yarn used is a wool yarn chemically treated for machine washability and garments knit from it generally would be outdoors or athletic wear and therefore unlikely to be subject to complex washing procedures. Additionally, manipulating the fabric would be contrary with observing natural skew.

When the samples had dried for 24 hours, they were cut apart. In order to achieve a high-quality image of the samples, it was necessary that each sample lay flat on the scanner bed. Steaming was performed at 130ºC and minimized to what was necessary to achieve a flat sample. Each sample was allowed to cool prior to scanning with a Zeutschel book scanner.

### 3.3.5 Measurements

The standard method for measuring skew in a knitted fabric is described in ASTM D3882-12. The test method requires cut pieces of fabric that are at least 400mm wide. Skew is measured using a straight edged ruler along the line of a course from selvedge to selvedge and compared to the distance of a line perpendicular to the selvedge that runs selvedge to selvedge (ASTM D3990-12, 2016). [See Figure 42]

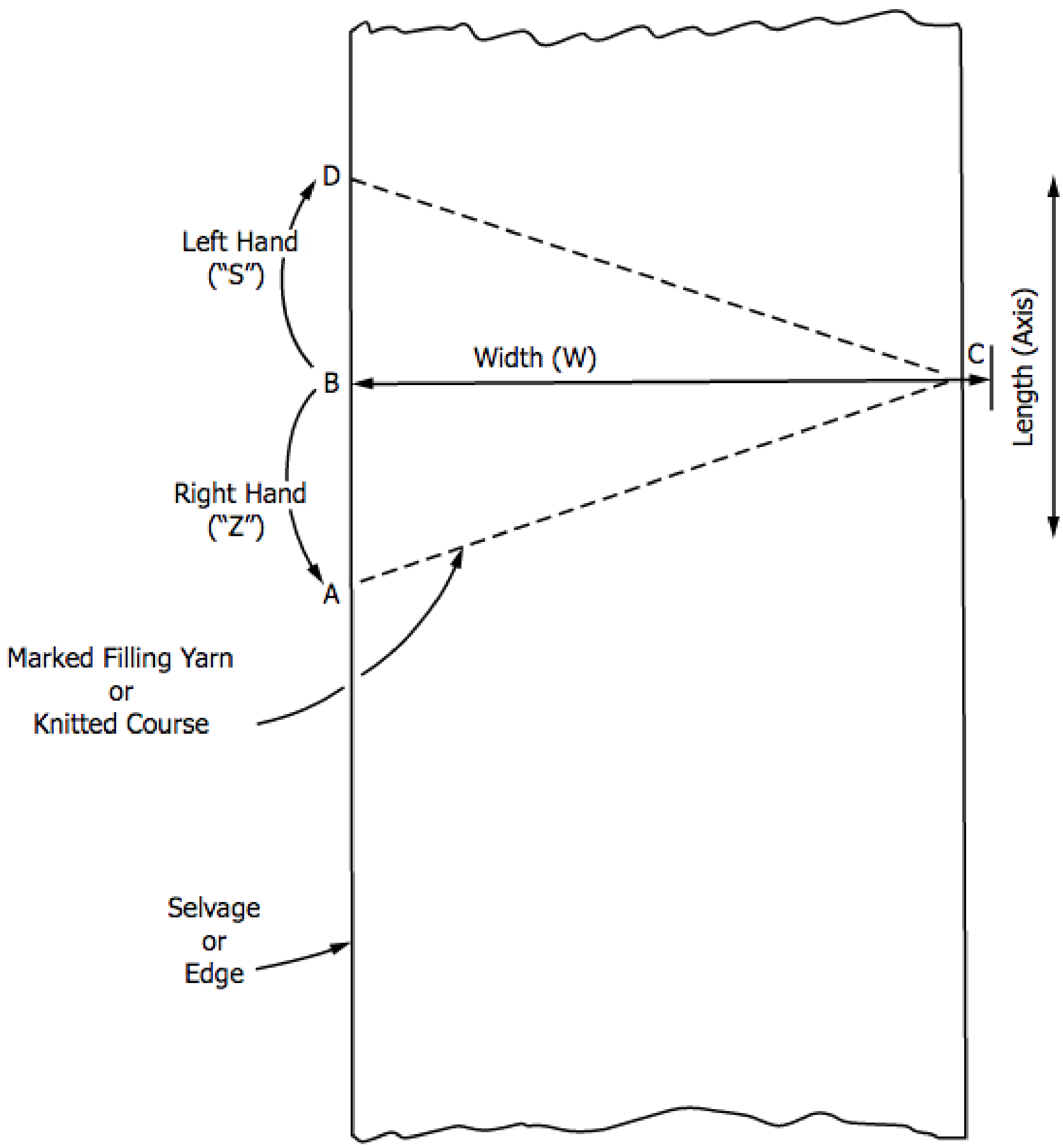


Figure 42. ASTM Test Method for Measuring Skew (ASTM D3882-12, 2016).

The concern with using this test method as written was twofold. Firstly, the test requires a lot of fabric. The purpose of this research is to examine the phenomena of skew within the context of integral or fully fashioned knitting which creates much smaller sections of fabric. A smaller test area more akin to a portion of a garment would more closely replicate the conditions of interest. Secondly, a physical straight edge lacks accuracy that is possible using digital measuring methods. If the test fabric is smaller, then this concern increases greatly.

Image based software is an established tool for describing knit fabric properties such as calculating color coverage in an analysis of resist dye techniques, change in knit shape through steps in the finishing process, and dimensional analysis comparing stitch patterns' effect on armscye shaping (Choi & Powell, 2008; Ruan, 2011). Previous studies involved pinning the specimens to align courses and wales to a grid (Ruan, 2011). This study is examining the skew of fabric, so stretching and pinning the fabric is precisely antithetical to the research.

In light of those concerns, a methodology was constructed which incorporated ASTM D3882-12 and image based software.  Samples were scanned using a Zeutschel book scanner and Autodesk AutoCAD2016 software used to measure the angle of intersection between courses and wales, perimeter, and area. The perimeter and area measurements were used to cross check the accuracy of the angle measurements.

Samples were placed flat in the Zeutschel book scanner. The file output for the Zeutschel book scanner is a multipage TIFF file where each page is a single scanned sample. The multipage TIFF file was separated using Preview (Mac OS) into five individual JPEG files with zero compression. The JPEG files were then inserted as a Raster Image Reference into Autodesk AutoCAD 2016 for Mac. Processing the sample scans in this way preserved the original dimensions of the scanned file.

In Autodesk AutoCad2016 the Polyline tool was used to trace along the edge of the sample fabric. The boundary line between the links-links stitch and the sample texture was distinctly visible in all samples. Two tracings were made. The first tracing followed all of the curves and distortions along the line. The second tracing made a quadrilateral figure aligning to the sample fabric as closely as possible. The Inquiry: Area tool was measure the area and perimeter of both tracings.

The first tracing provides a very accurate measurement of the sample texture area. [Figure 43] Selections could be made accurate to the individual half-stitch. However, the polygon that resulted had hundreds of sides and any single angle measurement would be meaningless.

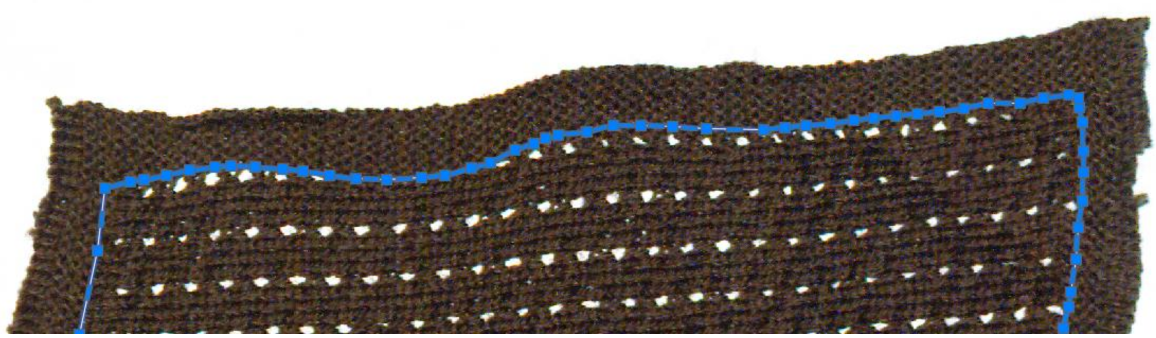

Figure 43 First Polyline Tracing

The second tracing produced easily measurable angles but with less accuracy to the true dimensions of the sample. [Figure 44] To determine the accuracy of the second tracing, the area and perimeter measurements were compared between each tracing method.

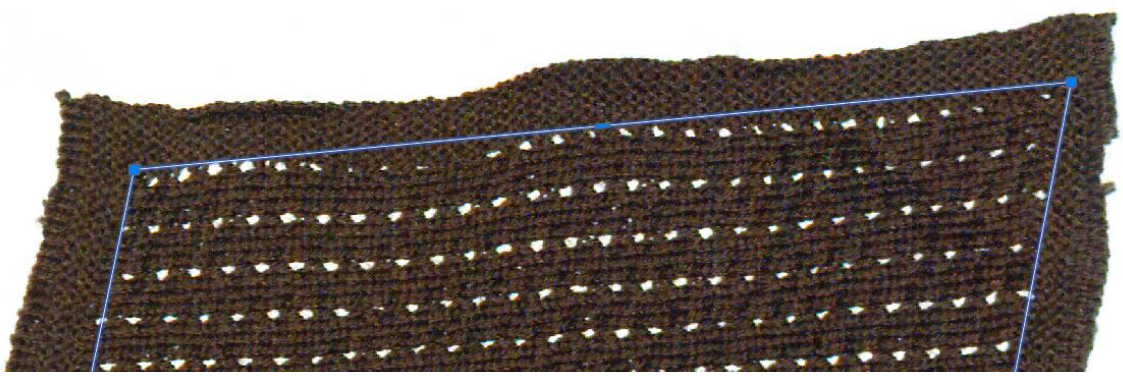

Figure 44 Second Polyline Trace

The two measures were compared using difference and variance. [See Table 1] All of the samples were measured so each average in Table 1 is an average of five measures. Difference was used to determine the dissimilarity between the two measures. If the measurement system was accurate then the measures should be identical or very close together.

The Control sample had a difference between averages of .4475cm$^2$. Only two treatment levels (Grid 3.125% and Paired 25%) had average difference of greater then 3cm$^2$. The Control sample was presumed to be possesses no skew due to its lack of pitch stitches. The difference between averages of the control sample is therefore an indicator of how much distortion was present due to the highly pliable nature of knitting fabric. Interestingly, several samples had less distortion then the control sample, which may indicate that those samples were less pliable and more dimensionally stable.

Similarly, variance was also used as a diagnostic tool. Knitting creates a highly pliable fabric and the tested phenomena was presumed large so 5% variance between the average first and average second tracing was determined to be the rejection point where a sample set would be rejected. The Control sample had a variance between averages of .0914%. Even the two sets with very large difference between levels were well within the rejection point of 5%. None of the sample sets were rejected for reasons of inaccuracy. [See Table 1]

Knitting is easily distorted and methods of regulating knitted fabric shape such as blocking and pinning had been rejected. The measurement method passed the benchmark of 5% variance for the control sample, which indicates that it is robust to the variation between knit fabric samples without additional dimensional distortion. The measurement method passed the benchmark of 5% variance for the experimental samples, which indicates that it is robust to the variation caused by skewness within knit fabric samples.

Table 1. Comparison of the Average Area Measurements per Data Set

| | | Average Area $cm^2$ | | | |
|---|---|---|---|---|---|
| | | **Quad** | **Poly** | **Difference** | **Variance** |
| **Control** | 0% | 489.2472 | 489.6947 | 0.4475 | 0.0914 |
| **Paired** | 25% | 320.6113 | 328.8303 | 8.2190 | 2.5311 |
| | 12.50% | 465.1494 | 467.0305 | 1.8810 | 0.4036 |
| | 6.25% | 496.4381 | 495.2910 | 1.1471 | 0.2313 |
| | 3.125% | 496.2671 | 498.3899 | 2.1228 | 0.4268 |
| **Grid** | 25% | 413.4312 | 413.0411 | 0.3901 | 0.0944 |
| | 12.50% | 491.3415 | 491.3924 | 0.0509 | 0.0104 |
| | 6.25% | 482.2772 | 482.6732 | 0.3960 | 0.0821 |
| | 3.125% | 444.2023 | 455.3131 | 11.1109 | 2.4704 |
| **Staggered** | 25% | 421.2698 | 420.5739 | 0.6960 | 0.1653 |
| | 12.50% | 486.6055 | 487.1873 | 0.5818 | 0.1195 |
| | 6.25% | 480.6879 | 480.1554 | 0.5326 | 0.1109 |
| | 3.13% | 487.9527 | 486.4238 | 1.5288 | 0.3138 |
| **Average** | | 459.6524 | 461.2305 | 2.2388 | 0.5424 |

Some sample sets were rejected for knitting flaws. Initially the range of pitch stitch percentages went from 3.125% to 50%. However, all three arrangements at 50% pitch stitches were rejected. The Staggered arrangement at 50% knit with a large flaw along the right side. In some samples, yarn was broken, and all samples showed a large drop stitch fault. [Figure 45]

Figure 45. Staggered arrangement at 50% pitch stitches.

Arranging stitches in a Paired or Grid arrangement proved problematic at 50% pitch stitches. To create a paired arrangement the pitch stitches would need to be staggered, which would prevent the set from being compared to a grid arrangement. More pressingly, the APEX SDS-ONE software reported such a high likelihood of broken needles that knitting it was rejected. A grid arrangement was prepared at 50% pitch stitches. [See Figure 46] However, at that pitch stitch density entire rows of pitched stitches alternated with rows of jersey. The samples knit well, but did not produce a mesh and the samples were rejected.

Figure 46. Grid Arrangement at 50% pitch stitches.

The highest variance in Area was in the sample Paired 25%, which presented 2.53% variance. The highest variance in perimeter was with the sample Staggered 25%, which presented 2.71% variance. Full calculation tables are presented in Appendix 1. That both of these samples are at the highest tested percentage is discussed in Further Research.

# 4. EXPERIMENTAL RESULTS

## 4.1. SO1: To determine the effect of increasing the percentage of single pitch right stitches within a jersey fabric on the skew of a fabric sample within a specific arrangement.

Results indicated that increasing the percentage of pitched stitches within a sample increased the difference between the measured angle of intersection between wales and courses from 90º in all three data sets. [See Figure 47]

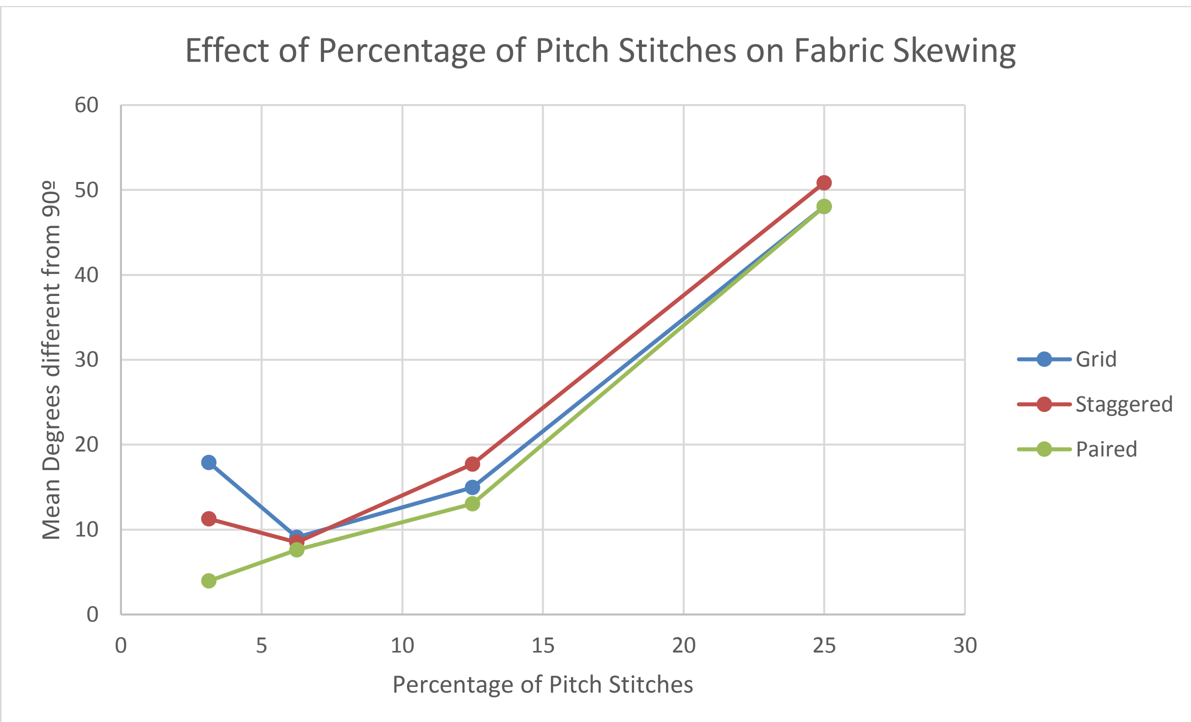


Figure 47. Effect of percentage of Pitch Stitches on Fabric Skewing

Increasing the number of pitched stitches arranged in pairs increased the amount of skew. [Figure 48] The Paired set was the only set for which the difference in skew was consistently an increase as percentage of pitch stitches increased. The consistent rise in skew results in a regression curve that is a 2nd order polynomial. Second order polynomials have a single extrema and the highest exponent in the equation is $x^2$.

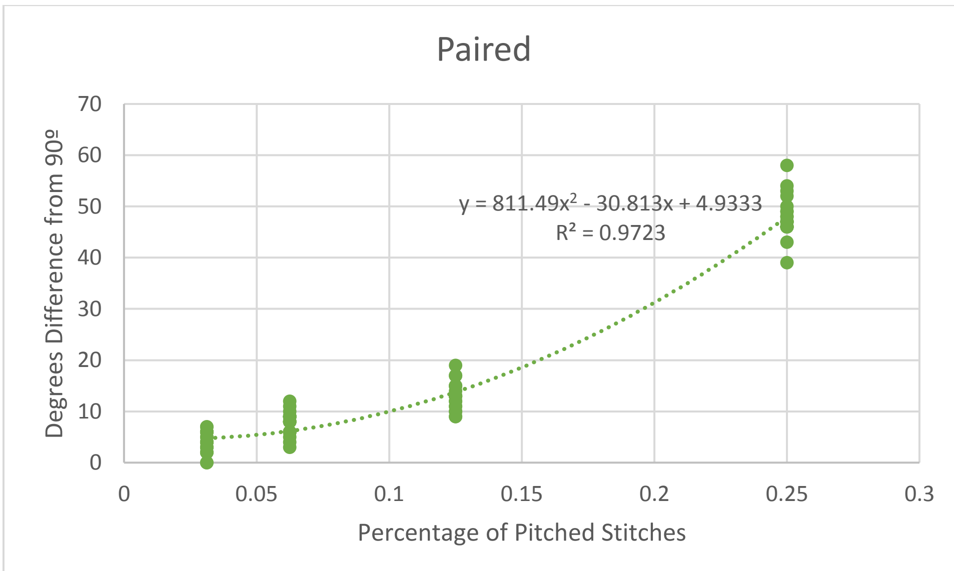


Figure 48. Skew at different percentages of paired stitches.

Increasing the percentage of pitched stitches arranged in a staggered arrangement generally increased the amount of skew. [See Figure 49] The staggered arrangement set showed a decrease in skew moving from 3.125% to 6.25%.

The regression line is a 3rd order polynomial, similar to the Grid arrangement and one order higher than the Paired arrangement. Third order polynomials have two extrema, which accommodates the decrease of skew between 3.125% and 6.25%. The decrease of skew between 3.125% and 6.25%  could also have been accommodated by a second order polynomial with a minimum between 6.25% and 12.5%. However, calculating that regression resulted in a higher $R^2$ value then with third order polynomial.

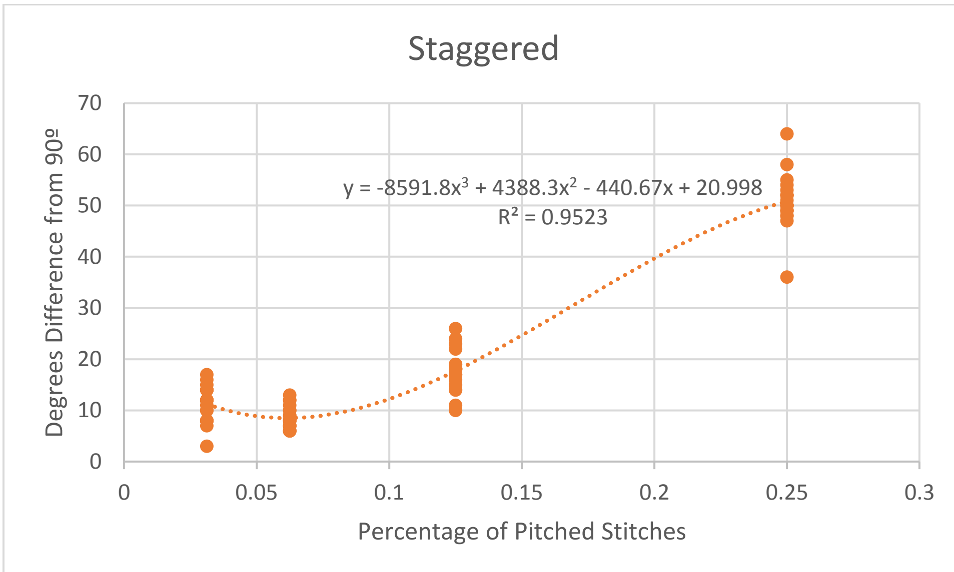


Figure 49 Skew at different percentages of staggered pitch stitches.

Increasing the percentage of pitched stitches arranged in a grid arrangement generally increased the amount of skew. [Figure 50] The grid arrangement set showed a decrease in skew moving from 3.125% and 6.25%. The regression line is a 3rd order polynomial, similar to the staggered arrangement and one order higher than the Paired arrangement.

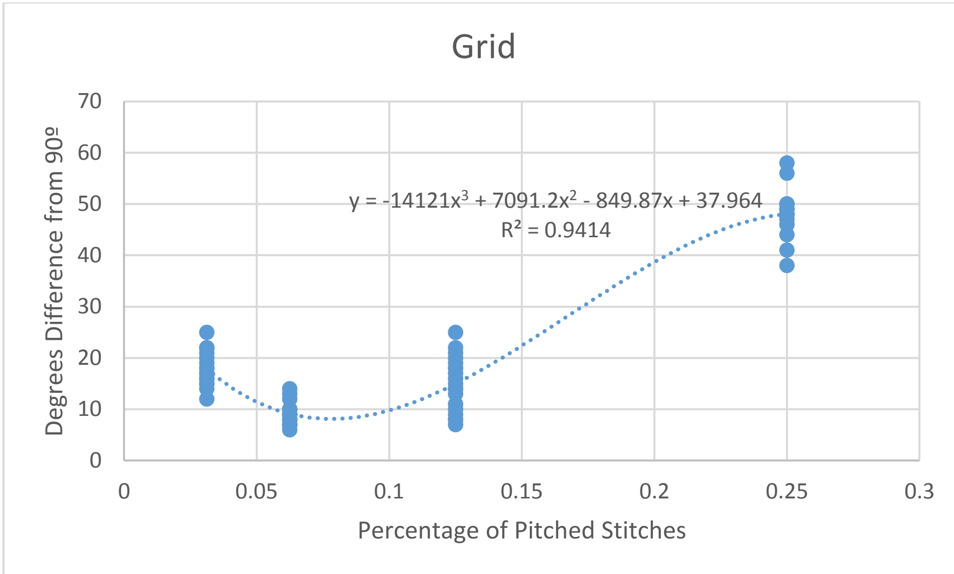


Figure 50. Skew at Different Percentages of Gridded Pitch Stitches

A much larger study would be needed to describe a more precise relationship. The large change between the 25% and 12.5% points could be better defined with more points. More points clustered around 3.125% could also better define the anomalous results at that density. As a general case, increasing the percentage of pitch stitches does increase the skew of the finished piece.

**4.2. SO2: Sub Objective Two: To determine the effect of doubling the number of single pitch right stitches within a course of knitting on the skew of fabric sample.**

Sub Objective Two compared grid arrangements to staggered arrangements at each of the four stitch percentages. Sub Objective One established that each stitch percentage has unique dimensional features and so each stitch percentage was treated as a separate statistical population. An F-test was undertaken, which examines the means under comparison to determine if they are different enough to have reasonably come from different population samples. [Table 2, see Appendix 2 for complete calculations] At each stitch percentage, the average angle difference from 90º was examined. At each stitch percentage, there was not significant variation to prove that the means come from different population samples. Figure 51 demonstrates the overlap between the populations.

Table 2. Calculations for the F-Test of the 25% Stitch Percentage.

| **F-Test Two-Sample for Variances** | | | |
|---|---|---|---|
| **25.000%** | | | |
| **Descriptive Statistics** | | | |
| | Staggered | Grid | |
| Sample size | 20 | 20 | |
| Mean | 50.85 | 48.05 | |
| Variance | 27.60789 | 18.57632 | |
| Standard Deviation | 5.25432 | 4.31003 | |
| Mean Standard Error | 1.1749 | 0.96375 | |
| **Summary** | | | |
| F | 1.48619 | F Critical value (5%) | 2.16825 |
| p-level 1-tailed | 0.1978 | p-level 2-tailed | 0.39559 |
| | | | |
| H0 (5%)? | **Accepted** | | |

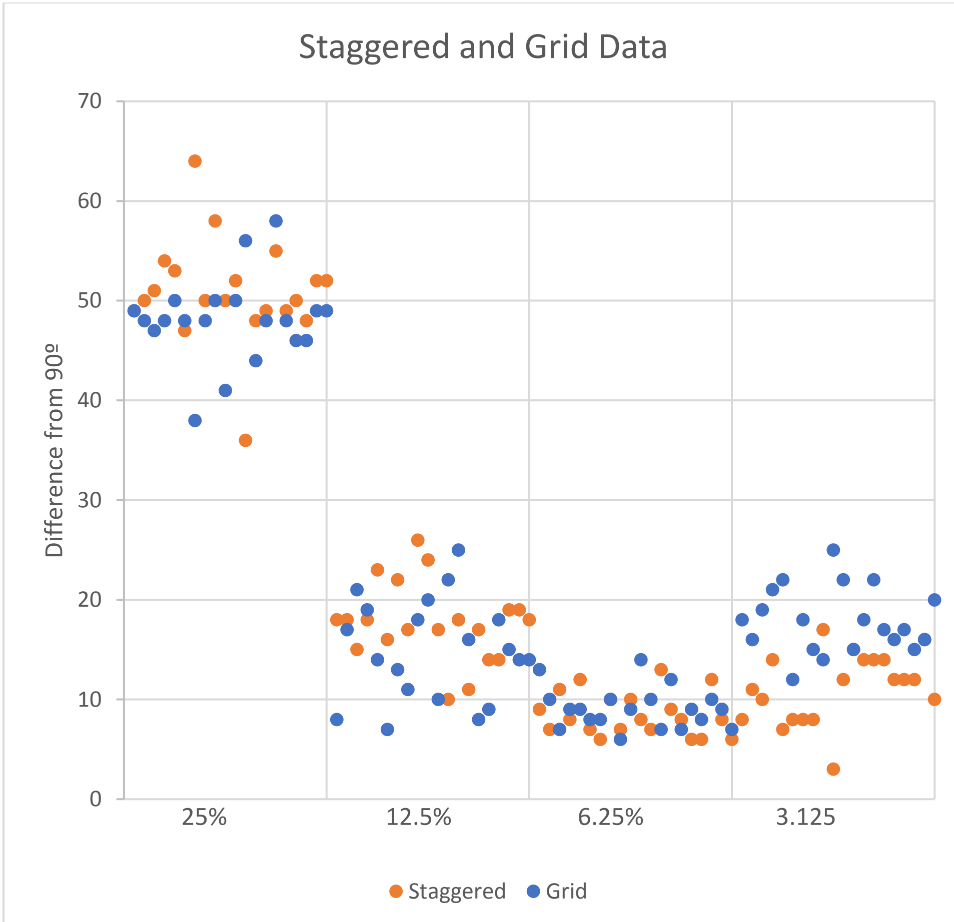


Figure 51. Overlap between Grid and Staggered Data

No difference was found in skewness between patterns in a grid arrangement and patterns arranged in a staggered arrangement. The difference in design between these groups is the distribution of the pitch stitches. The grid arrangement has more pitch stitches in each course that has pitch stitches. The staggered arrangement has a pitch stitch distribution that is more even. At the same pitch stitch density a grid arrangement has twice as many pitch stitches per course then the staggered arrangement. If the grid arrangements had skewed more then it would imply that pitching stitches closer together aggregates the skew effect.

However, no difference was found between the two arrangements. The results imply that there is no aggregate effect of placing pitch stitches close to each other.

### 4.3. SO3: To determine the effect of halving the percentage of single pitched stitches per mesh void on the skew of the fabric sample.

An F-test was undertaken, which examines the means under comparison to determine if they are different enough to have reasonably come from different population samples. Densities 25% and 6.25% did not pass the F-test, as there was no significant variation to indicate that the means came from different population samples. At 12.5% and 3.125% density, the F tests were passed and a T-test was performed. Full calculation tables are in Appendix 3.

At 3.125% there is a very clear difference between populations: the mean of Grid is 17.9º skewed and the mean of Paired is 3.95º skewed. The T-test confirmed this disparity. [Tables 3-4] Additionally, visual analysis of the data shows clearly separated point clusters. [Figure 52] At a density of 3.125% there is a greater distortion in a Grid arrangement than in a Paired arrangement.

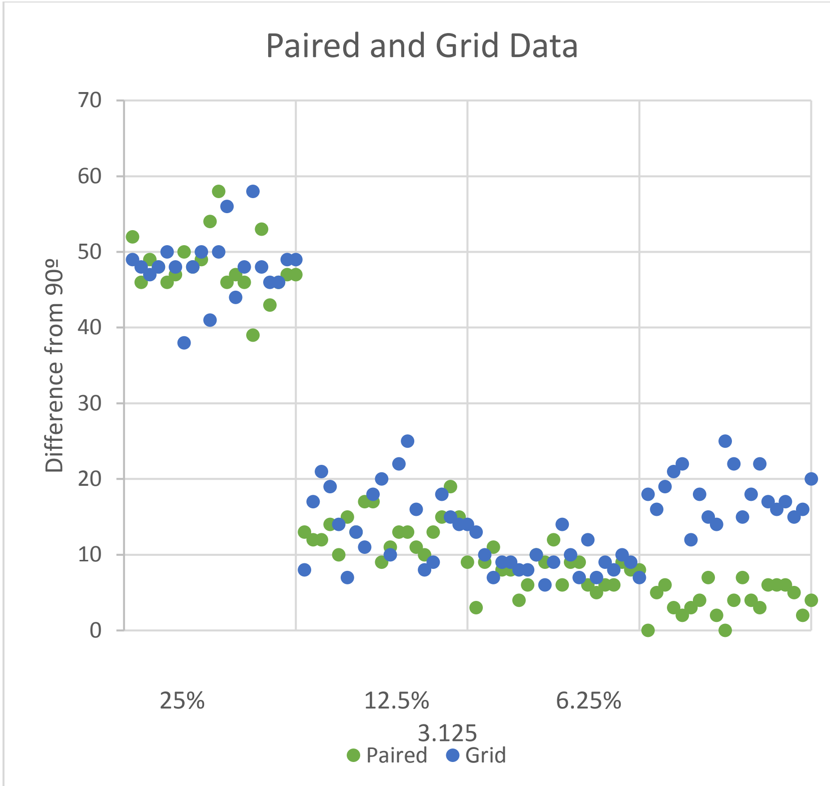


Figure 52. Overlap between paired and grid data.

Table 3. F-Test of Paired v. Grid

| F-Test Two-Sample for Variances | | | |
|---|---|---|---|
| **3.125%** | | | |
| **Descriptive Statistics** | | | |
| | **Paired** | **Grid** | |
| Sample size | 20 | 20 | |
| Mean | 3.95 | 17.9 | |
| Variance | 4.36579 | 10.72632 | |
| Standard Deviation | 2.08945 | 3.27511 | |
| Mean Standard Error | 0.46721 | 0.73234 | |
| **Summary** | | | |
| F | 2.4569 | F Critical value (5%) | 2.16825 |
| p-level 1-tailed | 0.02853 | p-level 2-tailed | 0.05707 |
| | | | |
| H0 (5%)? | **Rejected** | | |

| T-Test | | | | |
|---|---|---|---|---|
| 3.125% | | | | |
| **Descriptive Statistics** | | | | |
| | **Sample size** | **Mean** | **Standard Deviation** | **Variance** |
| Paired | 20 | 3.95 | 2.08945 | 4.36579 |
| Grid | 20 | 17.9 | 3.27511 | 10.72632 |
| **Paired two-sample t-test** | | | | |
| Degrees of Freedom | | | 19 | |
| Hypothesized Mean Difference | | | 0 | |
| Pooled Variance | | | 7.54605 | |
| Test Statistics | | | 13.68343 | |
| Pearson Correlation Coefficient | | | -0.41609 | |
| **Two-tailed distribution** | | | | |
| p-level | 2.74E-11 | Critical Value (5%) | 2.09302 | |
| **One-tailed distribution** | | | | |
| p-level | 1.37E-11 | Critical Value (5%) | 1.72913 | |
| **G-criterion** | | | | |
| Test Statistics | 1.395 | Critical Value (5%) | 0.143 | |
| p-level | 0 | | | |
| **Pagurova criterion** | | | | |
| Ratio of variances parameter | | | 0.28928 | |
| Test Statistics | 16.05884 | Critical Value (5%) | 0.0632 | |
| p-level | 1 | | | |

Table 4. T Test of Paired vs. Grid at 3.125%

The 12.5% density was less clear. [Tables 5-6] The means were very close with a 1.9º difference. The differentiation between the populations comes from the huge differences in variance between the two populations, with Grid having a variance of 26 and Paired having a variance of 7.42. Visual analysis of the data shows the paired data clusters within a dispersed group of Grid points. [Figure 53]

Table 5. F-Test of Paired vs. Grid at 12.5%

| F-Test Two-Sample for Variances | | | |
|---|---|---|---|
| **12.500%** | | | |
| **Descriptive Statistics** | | | |
| | **Paired** | **Grid** | |
| Sample size | 20 | 20 | |
| Mean | 13.05 | 14.95 | |
| Variance | 7.41842 | 26.05 | |
| Standard Deviation | 2.72368 | 5.10392 | |
| Mean Standard Error | 0.60903 | 1.14127 | |
| **Summary** | | | |
| F | 3.51153 | F Critical value (5%) | 2.16825 |
| p-level 1-tailed | 0.00438 | p-level 2-tailed | 0.00876 |
| | | | |
| H0 (5%)? | **Rejected** | | |

Table 6. T-Test of Paired vs. Grid at 12.5%

| **T-Test** | | | | |
|---|---|---|---|---|
| **12.500%** | | | | |
| **Descriptive Statistics** | | | | |
| | **Sample size** | **Mean** | **Standard Deviation** | **Variance** |
| Paired | 20 | 13.05 | 2.72368 | 7.41842 |
| Grid | 20 | 14.95 | 5.10392 | 26.05 |
| **Paired two-sample t-test** | | | | |
| Degrees of Freedom | | | 19 | |
| Hypothesized Mean Difference | | | 0 | |
| Pooled Variance | | | 16.73421 | |
| Test Statistics | | | 1.45972 | |
| Pearson Correlation Coefficient | | | -0.01495 | |
| **Two-tailed distribution** | | | | |
| p-level | 0.1607 | Critical Value (5%) | 2.09302 | |
| **One-tailed distribution** | | | | |
| p-level | 0.08035 | Critical Value (5%) | 1.72913 | |
| **G-criterion** | | | | |
| Test Statistics | 0.13571 | Critical Value (5%) | 0.143 | |
| p-level | 0.05628 | | | |
| **Pagurova criterion** | | | | |
| Ratio of variances parameter | | | 0.22165 | |
| Test Statistics | 1.46876 | Critical Value (5%) | 0.06326 | |
| p-level | 0.84712 | | | |

There appears to be a difference between these two fabrics but that difference does not appear to be skewness. The high variance of the 12.5% grid suggests a very deformable fabric in comparison to 12.5% paired. Furthermore, the context of this study is to reduce the required number of prototypes in knit design. Comparison between the grid and paired arrangements at this stitch density does not result in greater certainty of finished dimensions.

### 4.2.4. Conclusions

This study examined the skew of fabric. In the preliminary phase of this research pitch stitches were identified as a cause of skew in knit mesh fabrics. Using equal numbers of left and right pitched stitches was identified as a method to eliminate skew in knit mesh.

In the experimental phase of the research, three objectives were pursued that investigated specific characteristics of knit mesh. Firstly, it was determined that there is a relationship between the number of pitch stitches within a sample and the skew of the sample. While generally increasing the number of pitch stitches increased skew, the relationship was not linear and the relationship varied between pattern types. The Grid and the Staggered arrangement both regressed as cubic functions, which showed an increase of skew at the lowest tested percentage of pitch stitches.

Secondly, it was determined that the number of pitched stitches per course was insignificant. Samples with twice as many pitched stitches per course skewed about the same amount as samples with half as many pitched stitches per course and the same total percentage of pitched stitches. Thirdly, it was determined that the number of pitched stitches per mesh hole was significant only at the lowest tested percentage of pitched stitch.

Establishing that the number of pitched stitches changes the skew of the fabric more than the concentration or number of voids is interesting because it is precisely contrary to the phenomena in hand knitting. Concentration of decreases and increases create large curvilinear patterns within hand knitting.  Hand knit techniques most similar to the paired arrangement are used to create fabric with a pronounced biased skew.  It is of course possible that examination of different mesh patterns would produce different results but the contrast remains peculiar.

At each percentage of pitch stitches, the amount of skew within the samples is very similar through all three sets. The proposed application of this research is to assist knit designers in creating accurate initial design decisions to bridge the limitations of digital simulation. The results of this study imply that a reasonable initial dimensional estimation could be attained by comparing a proposed stitch pattern to one of similar pitch percentages within a designer’s library of already knit samples.

### 4.3. Further Research

The samples knitted exhibited a wide variety of differing characteristics. The lowest densities of knit stitches provide anomalous data that imply the presence of compounding variables. Further research to quantify the differences will lead to a better understanding of knit mesh and better predictive abilities.

Hand properties differed substantially between samples. The lower densities of fabric had a very smooth hand but the higher densities had pronounced raised texture that had high surface roughness. The middle textures appeared to be the most elastic. A detailed study of hand properties of knitted mesh samples is clearly needed to illuminate the myriad differences between these samples. Properties such as extensibility, bending hysteresis, surface friction, shear, and surface roughness are of particular interest. Surface friction and surface roughness were noted as different in the fabric samples used in this study. Extensibility, bending hysteresis, and shear properties could also contribute to deformation and skew of samples.

The change between 3.125% pitched stitches and 6.25% pitched stitches is anomalous. All arrangements showed an increase in skew in the lowest density, and it was only 3.125% where a difference was found between stitch arrangements. It is possible that this difference is related to another fabric property such as hysteresis or shear. Furthermore, the 6.25% data sets all had a much smaller range compared to 3.125% or 12.5%. This result seems to indicate that the skew of the fabric may not solely be caused by pitched stitches. There appears to be something that changes in the fabric beyond simply percentage of pitched stitches that is affecting the final fabric shape. Knit fabric properties are myriad and complex and 3.125% data confirms that pitch stitch percentage is only one of the factors affecting fabric size.

This study also only examined three very simple arrangements. There are many more ways to pitch a stitch – including but not limited to pitching backside stitches, pitching more than one loop, and pitching with additional machine movements such as kickback (Shima, 2016). All of these could have different effects on the dimensions of the fabric. The difference in arrangement of stitches was rejected for three arrangements examined in this study but that does not imply that all stitch arrangements have equal effect on skew.

A continuation in studies of this nature will require a refinement of measurements. The double tracing method used in AutoCAD was successful at simplifying the shape of the fabric sufficient for angle measurements to be taken while maintaining <95% area and perimeter accuracy. This method required a large expenditure of time, and required that the researcher have skill in reading fabric and in using the AutoCAD software. Automating this process or eliminating it or reducing to a single step will make replication far more feasible.

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# APPENDICES

# APPENDIX 1

| Sample | | Absolute value of Angle Measurement - 90º | | | | | |
|---|---|---|---|---|---|---|---|
| Arrangement | Density | A | B | C | D | Average Per Sample | Average per Set |
| | | 3 | 2 | 7 | 6 | 4.5 | 4.05 |
| | | 6 | 7 | 10 | 11 | 8.5 | |
| | | 0 | 0 | 2 | 2 | 1 | |
| | | 3 | 3 | 3 | 3 | 3 | |
| Control | 0 | 4 | 3 | 4 | 2 | 3.25 | |
| | | 52 | 47 | 58 | 53 | 52.5 | 48.05 |
| | | 46 | 50 | 46 | 43 | 46.25 | |
| | | 49 | 48 | 47 | 46 | 47.5 | |
| | | 48 | 49 | 46 | 47 | 47.5 | |
| | 25 | 46 | 54 | 39 | 47 | 46.5 | |
| | | 0 | 3 | 4 | 6 | 3.25 | 3.95 |
| | | 5 | 4 | 7 | 6 | 5.5 | |
| | | 6 | 7 | 4 | 5 | 5.5 | |
| | | 3 | 2 | 3 | 2 | 2.5 | |
| | 3.125 | 2 | 0 | 6 | 4 | 3 | |
| | | 13 | 15 | 11 | 13 | 13 | 13.05 |
| | | 12 | 13 | 13 | 15 | 13.25 | |
| | | 12 | 17 | 13 | 19 | 15.25 | |
| | | 14 | 17 | 11 | 15 | 14.25 | |
| | 12.5 | 10 | 9 | 10 | 9 | 9.5 | |
| | | 3 | 4 | 6 | 6 | 4.75 | 7.6 |
| | | 9 | 6 | 9 | 6 | 7.5 | |
| | | 11 | 10 | 9 | 9 | 9.75 | |
| | | 8 | 9 | 6 | 8 | 7.75 | |
| Paired | 6.25 | 8 | 12 | 5 | 8 | 8.25 | |

| Sample | | Absolute value of Angle Measurement - 90º | | | | | |
|---|---|---|---|---|---|---|---|
| **Arrangement** | **Density** | **A** | **B** | **C** | **D** | **Average Per Sample** | **Average per Set** |
| | | 8 | 7 | 10 | 9 | 8.5 | 14.95 |
| | | 17 | 13 | 22 | 18 | 17.5 | |
| | | 21 | 11 | 25 | 15 | 18 | |
| | | 19 | 18 | 16 | 14 | 16.75 | |
| | 12.5 | 14 | 20 | 8 | 14 | 14 | |
| | | 18 | 12 | 22 | 16 | 17 | 17.9 |
| | | 16 | 18 | 15 | 17 | 16.5 | |
| | | 19 | 15 | 18 | 15 | 16.75 | |
| | | 21 | 14 | 22 | 16 | 18.25 | |
| | 3.125 | 22 | 25 | 17 | 20 | 21 | |
| | | 13 | 8 | 14 | 9 | 11 | 9.1 |
| | | 10 | 8 | 10 | 8 | 9 | |
| | | 7 | 10 | 7 | 10 | 8.5 | |
| | | 9 | 6 | 12 | 9 | 9 | |
| | 6.25 | 9 | 9 | 7 | 7 | 8 | |
| | | 49 | 48 | 50 | 48 | 48.75 | 48.05 |
| | | 48 | 38 | 56 | 46 | 47 | |
| | | 47 | 48 | 44 | 46 | 46.25 | |
| | | 48 | 50 | 48 | 49 | 48.75 | |
| Grid | 25 | 50 | 41 | 58 | 49 | 49.5 | |

| Sample | | Absolute value of Angle Measurement - 90º | | | | | |
|---|---|---|---|---|---|---|---|
| **Arrangement** | **Density** | **A** | **B** | **C** | **D** | **Average Per Sample** | **Average per Set** |
| | | 8 | 8 | 12 | 12 | 10 | 11.25 |
| | | 11 | 8 | 15 | 12 | 11.5 | |
| | | 10 | 8 | 14 | 12 | 11 | |
| | | 14 | 17 | 14 | 16 | 15.25 | |
| | 3.125 | 7 | 3 | 14 | 10 | 8.5 | |
| | | 18 | 16 | 17 | 14 | 16.25 | 17.7 |
| | | 18 | 22 | 10 | 14 | 16 | |
| | | 15 | 17 | 18 | 19 | 17.25 | |
| | | 18 | 26 | 11 | 19 | 18.5 | |
| | 12.5 | 23 | 24 | 17 | 18 | 20.5 | |
| | | 49 | 47 | 52 | 49 | 49.25 | 50.85 |
| | | 50 | 64 | 36 | 50 | 50 | |
| | | 51 | 50 | 48 | 48 | 49.25 | |
| | | 54 | 58 | 49 | 52 | 53.25 | |
| | 25 | 53 | 50 | 55 | 52 | 52.5 | |
| | | 9 | 7 | 8 | 6 | 7.5 | 8.5 |
| | | 7 | 6 | 7 | 6 | 6.5 | |
| | | 11 | 10 | 13 | 12 | 11.5 | |
| | | 8 | 7 | 9 | 8 | 8 | |
| Staggered | 6.125 | 12 | 10 | 8 | 6 | 9 | |

| Sample | | Area | | | | Perimeter | | | |
|---|---|---|---|---|---|---|---|---|---|
| Arrangement | Density | Poly Set Average | Quad Set Average | Difference | % Variance | Poly Set Average | Quad Set Average | Difference | |
| Control | 0 | 489.6947 | 489.24718 | 0.44752 | 0.09142933 | 88.9003 | 88.83732 | 0.06298 | 0.070868508 |
| Paired | 25 | 328.83028 | 320.61132 | 8.21896 | 2.531085166 | 90.00756 | 87.74494 | 2.26262 | 2.545809482 |
| | 3.125 | 498.38988 | 496.2671 | 2.12278 | 0.426836596 | 90.6845 | 89.64604 | 1.03846 | 1.151729485 |
| | 12.5 | 467.03048 | 465.14944 | 1.88104 | 0.403578743 | 88.87542 | 87.9149 | 0.96052 | 1.08662058 |
| | 6.25 | 495.291 | 496.4381 | 1.1471 | 0.231333335 | 89.7312 | 89.784 | 0.0528 | 0.058825102 |
| Grid | 12.5 | 491.39238 | 491.34152 | 0.05086 | 0.010350717 | 91.99682 | 91.24002 | 0.7568 | 0.826034765 |
| | 3.125 | 455.31314 | 444.20226 | 11.11088 | 2.470414625 | 90.84108 | 88.65588 | 2.1852 | 2.434804467 |
| | 6.25 | 482.67318 | 482.2772 | 0.39598 | 0.082072614 | 89.36294 | 88.93618 | 0.42676 | 0.478701185 |
| | 25 | 413.04112 | 413.43124 | 0.39012 | 0.094406061 | 99.23748 | 100.76736 | 1.52988 | 1.529842978 |
| Staggered | 3.125 | 486.42382 | 487.95266 | 1.52884 | 0.313808888 | 89.85108 | 89.79618 | 0.0549 | 0.061119774 |
| | 12.5 | 487.18732 | 486.60548 | 0.58184 | 0.119499754 | 91.69408 | 91.13328 | 0.5608 | 0.61347492 |
| | 25 | 420.57386 | 421.26982 | 0.69596 | 0.16534186 | 101.57138 | 104.36464 | 2.79326 | 2.712745444 |
| | 6.125 | 480.15538 | 480.68794 | 0.53256 | 0.110852621 | 89.54234 | 88.88688 | 0.65546 | 0.734700292 |

# APPENDIX 2

| F-Test Two-Sample for Variances | | | |
|---|---|---|---|
| **25.000%** | | | |
| **Descriptive Statistics** | | | |
| | Staggered | Grid | |
| Sample size | 20 | 20 | |
| Mean | 50.85 | 48.05 | |
| Variance | 27.60789 | 18.57632 | |
| Standard Deviation | 5.25432 | 4.31003 | |
| Mean Standard Error | 1.1749 | 0.96375 | |
| **Summary** | | | |
| F | 1.48619 | F Critical value (5%) | 2.16825 |
| p-level 1-tailed | 0.1978 | p-level 2-tailed | 0.39559 |
| | | | |
| H0 (5%)? | **Accepted** | | |

| F-Test Two-Sample for Variances | | | |
|---|---|---|---|
| **12.500%** | | | |
| **Descriptive Statistics** | | | |
| | Staggered | Grid | |
| Sample size | 20 | 20 | |
| Mean | 17.7 | 14.95 | |
| Variance | 15.90526 | 26.05 | |
| Standard Deviation | 3.98814 | 5.10392 | |
| Mean Standard Error | 0.89178 | 1.14127 | |
| **Summary** | | | |
| F | 1.63782 | F Critical value (5%) | 2.16825 |
| p-level 1-tailed | 0.14549 | p-level 2-tailed | 0.29098 |
| | | | |
| H0 (5%)? | **Accepted** | | |

| F-Test Two-Sample for Variances | | | |
|---|---|---|---|
| 6.250% | | | |
| Descriptive Statistics | | | |
| | Staggered | Grid | |
| Sample size | 20 | 20 | |
| Mean | 9.1 | 8.5 | |
| Variance | 4.30526 | 4.78947 | |
| Standard Deviation | 2.07491 | 2.18849 | |
| Mean Standard Error | 0.46396 | 0.48936 | |
| **Summary** | | | |
| F | 1.11247 | F Critical value (5%) | 2.16825 |
| p-level 1-tailed | 0.40936 | p-level 2-tailed | 0.81871 |
| | | | |
| H0 (5%)? | **Accepted** | | |

| F-Test Two-Sample for Variances | | | |
|---|---|---|---|
| 3.125% | | | |
| Descriptive Statistics | | | |
| | Staggered | Grid | |
| Sample size | 20 | 20 | |
| Mean | 11.25 | 17.9 | |
| Variance | 12.30263 | 10.72632 | |
| Standard Deviation | 3.50751 | 3.27511 | |
| Mean Standard Error | 0.7843 | 0.73234 | |
| **Summary** | | | |
| F | 1.14696 | F Critical value (5%) | 2.16825 |
| p-level 1-tailed | 0.38407 | p-level 2-tailed | 0.76814 |
| | | | |
| H0 (5%)? | **Accepted** | | |

# APPENDIX 3

| F-Test Two-Sample for Variances | | | |
|---|---|---|---|
| 25.000% | | | |
| **Descriptive Statistics** | | | |
| | **Paired** | **Grid** | |
| Sample size | 20 | 20 | |
| Mean | 48.05 | 48.05 | |
| Variance | 16.47105 | 18.57632 | |
| Standard Deviation | 4.05845 | 4.31003 | |
| Mean Standard Error | 0.9075 | 0.96375 | |
| **Summary** | | | |
| F | 1.12782 | F Critical value (5%) | 2.16825 |
| p-level 1-tailed | 0.39795 | p-level 2-tailed | 0.79591 |
| | | | |
| H0 (5%)? | **Accepted** | | |

| F-Test Two-Sample for Variances | | | |
|---|---|---|---|
| 12.500% | | | |
| Descriptive Statistics | | | |
| | **Paired** | **Grid** | |
| Sample size | 20 | 20 | |
| Mean | 13.05 | 14.95 | |
| Variance | 7.41842 | 26.05 | |
| Standard Deviation | 2.72368 | 5.10392 | |
| Mean Standard Error | 0.60903 | 1.14127 | |
| **Summary** | | | |
| F | 3.51153 | F Critical value (5%) | 2.16825 |
| p-level 1-tailed | 0.00438 | p-level 2-tailed | 0.00876 |
| | | | |
| H0 (5%)? | **Rejected** | | |

| F-Test Two-Sample for Variances | | | |
|---|---|---|---|
| 6.250% | | | |
| Descriptive Statistics | | | |
| | **Paired** | **Grid** | |
| Sample size | 20 | 20 | |
| Mean | 7.6 | 9.1 | |
| Variance | 5.30526 | 4.30526 | |
| Standard Deviation | 2.30332 | 2.07491 | |
| Mean Standard Error | 0.51504 | 0.46396 | |
| **Summary** | | | |
| F | 1.23227 | F Critical value (5%) | 2.16825 |
| p-level 1-tailed | 0.32677 | p-level 2-tailed | 0.65354 |
| | | | |
| H0 (5%)? | **Accepted** | | |

| F-Test Two-Sample for Variances | | | |
|---|---|---|---|
| **3.125%** | | | |
| **Descriptive Statistics** | | | |
| | **Paired** | **Grid** | |
| Sample size | 20 | 20 | |
| Mean | 3.95 | 17.9 | |
| Variance | 4.36579 | 10.72632 | |
| Standard Deviation | 2.08945 | 3.27511 | |
| Mean Standard Error | 0.46721 | 0.73234 | |
| **Summary** | | | |
| F | 2.4569 | F Critical value (5%) | 2.16825 |
| p-level 1-tailed | 0.02853 | p-level 2-tailed | 0.05707 |
| | | | |
| H0 (5%)? | **Rejected** | | |

| T-Test | | | | |
|---|---|---|---|---|
| 3.125% | | | | |
| Descriptive Statistics | | | | |
| | **Sample size** | **Mean** | **Standard Deviation** | **Variance** |
| Paired | 20 | 3.95 | 2.08945 | 4.36579 |
| Grid | 20 | 17.9 | 3.27511 | 10.72632 |
| **Paired two-sample t-test** | | | | |
| Degrees of Freedom | | | 19 | |
| Hypothesized Mean Difference | | | 0 | |
| Pooled Variance | | | 7.54605 | |
| Test Statistics | | | 13.68343 | |
| Pearson Correlation Coefficient | | | -0.41609 | |
| **Two-tailed distribution** | | | | |
| p-level | 2.74E-11 | Critical Value (5%) | 2.09302 | |
| **One-tailed distribution** | | | | |
| p-level | 1.37E-11 | Critical Value (5%) | 1.72913 | |
| **G-criterion** | | | | |
| Test Statistics | 1.395 | Critical Value (5%) | 0.143 | |
| p-level | 0 | | | |
| **Pagurova criterion** | | | | |
| Ratio of variances parameter | | | 0.28928 | |
| Test Statistics | 16.05884 | Critical Value (5%) | 0.0632 | |
| p-level | 1 | | | |

| T-Test | | | | |
|---|---|---|---|---|
| **12.500%** | | | | |
| **Descriptive Statistics** | | | | |
| | **Sample size** | **Mean** | **Standard Deviation** | **Variance** |
| Paired | 20 | 13.05 | 2.72368 | 7.41842 |
| Grid | 20 | 14.95 | 5.10392 | 26.05 |
| **Paired two-sample t-test** | | | | |
| Degrees of Freedom | | | 19 | |
| Hypothesized Mean Difference | | | 0 | |
| Pooled Variance | | | 16.73421 | |
| Test Statistics | | | 1.45972 | |
| Pearson Correlation Coefficient | | | -0.01495 | |
| **Two-tailed distribution** | | | | |
| p-level | 0.1607 | Critical Value (5%) | 2.09302 | |
| **One-tailed distribution** | | | | |
| p-level | 0.08035 | Critical Value (5%) | 1.72913 | |
| **G-criterion** | | | | |
| Test Statistics | 0.13571 | Critical Value (5%) | 0.143 | |
| p-level | 0.05628 | | | |
| **Pagurova criterion** | | | | |
| Ratio of variances parameter | | | 0.22165 | |
| Test Statistics | 1.46876 | Critical Value (5%) | 0.06326 | |
| p-level | 0.84712 | | | |