COMPARISON OF TEXAS RAMBOUILLET SHEEP WITH MERINO F1 CROSSES AND THEIR WOOL AS IT UNDERGOES MANUFACTURING WITHIN THE UNITED STATES APPAREL INDUSTRY

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DEDICATION

The author wishes to dedicate this thesis to the Texas wool producers for their knowledge, guidance, and encouragement throughout her thesis work. Their perseverance through the volatility in the sheep and wool industry through the years amongst other hardships has been a true inspiration.

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The author wishes to express her sincere appreciation to Dr. Chris Lupton for initially designing the live-animal portion of this project and submitting the grant work to receive funding for this project as well as his continued guidance and support with the project once she took it over. Sincere appreciation is also expressed to Texas Department of Agriculture for the funding of this project; Dr. John Walker for the support for the fabric portion of the study; Dr. Dan Waldron and Dr. Ronald Pope at Texas A&M AgriLife Research for serving on my committee and the countless hours of support writing this thesis; Dr. Mike Salisbury and Dr. Cody Scott at Angelo State University for serving on this committee and their help and support of writing this thesis; Dr. Adam Parker for serving on my thesis committee; Mr. Faron Pfeiffer for his help and encouragement throughout her time at the wool lab.

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ABSTRACT

Due to rising feed and labor costs, producers raising range sheep prefer less management-intensive operations. This study aimed to increase income from traditional Texas Rambouillet ewes by increasing wool production and improving wool quality without causing a reduction in lamb production and without incurring increased inputs in the form of labor or nutrition by crossbreeding Texas Rambouillet ewes with Australian Merino sires. Additionally, the wool produced by both the Rambouillet (R) offspring and the Merino x Rambouillet (MR) offspring underwent additional testing throughout production and manufacturing of garments suitable for active wear clothing. Fiber diameter was decreased and total wool production and staple length were increased by the MR offspring compared to the R control animals. The R offspring exhibited greater weaning weights. In the fabric and garment testing, the MR and R wool performed very similarly and both are highly suitable for use in garments within the active wear market.

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INTRODUCTION

Income from wool production of range ewes is relatively minor in comparison to that from offspring raised by a ewe. However, when resources are scarce, increasing the wool production of a ewe flock is one way to increase profits with few extra management inputs. Due to current economic trends and rising feed and labor costs, producers raising range sheep are trying to emphasize less management-intensive operations. Increasing wool production and decreasing fiber diameter can increase profit from yearly wool sales. Some Merinos from Australia are reported to produce heavy fleeces with low fiber diameter (Cottle, 1991). Crossbreeding Rambouillet ewes with Merino rams is a strategy that may improve wool value. Unfortunately, prolificacy and fertility of ewes sired by Merino rams was lower than those sired by Rambouillet rams (Snowder *et al*., 1997a). Decreased weaning weights were also reported due to the smaller size of Australian Merino sheep used (Snowder *et al*., 1997b). However, the selection of Australian Merino sires with adequate genetic merit for growth, as well as fiber traits, has the potential to produce offspring that should produce considerably more wool with a smaller average fiber diameter than Rambouillet sheep are currently producing. Excessive wrinkling and the reduction of other important production traits relative to Rambouillet will be monitored in this study as those aspects are important to sheep producers in the United States.

Wool is sold by the producer mainly based on clean wool yield and the average fiber diameter. The smaller the fiber diameter, the higher the premium paid to the producer because it is considered to be higher quality wool. Some Australian Merino sheep have been bred to produce fleeces with a smaller fiber diameter and more wool than traditional Texas

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Rambouillet sheep. The ultimate goal of this study is to compare offspring from Merino and Rambouillet sires for wool production and other economically important traits when managed under western Texas range conditions. This project may lead to a method for US sheep producers to produce smooth-bodied sheep capable of growing more and finer wool without compromising the body composition and style of Texas Rambouillet sheep and without additional management practices being implemented into an operation.

Wool is a specialty fiber, due to its exceptional attributes and lower volumes worldwide when compared to most other fibers, especially cotton and polyester. Low average fiber diameter, staple wools (< 20µm and > 75mm) are always in high demand. New advancements in research and development are finding wool is suitable and often more desirable than synthetics in active wear garments (Simpson *et al*., 2002). The latest developments in wool textiles have led to the creation of lighter-weight and softer fabrics made with smaller diameter wool that are geared towards active and casual wear. These textiles exhibit the natural moisture absorption attributes including that a wool fiber can absorb up to 35% of its own weight in water at a high humidity before feeling wet (Collie *et al*., 1998). Small fiber diameter wool may be used to produce high-quality sports apparel, which has the ability to actively manage heat and moisture flows from the body under a variety of conditions. It also suppresses odors, has high abrasion resistance, is very durable, and delivers the highest levels of comfort and performance (Collie *et al*., 1998).

LITERATURE REVIEW

Rambouillet sheep were first imported to the United States from France, with the name ‘French Merino’ in the mid-1800s. The name, French Merino eventually changed over to Rambouillet around the late 1800s. This name was derived from the town and area where the sheep were raised in France, from a flock produced from some of the most elite Merino sheep that originated from Spain. Since the first Rambouillet sheep were imported to the United States, producers have focused on raising large frame, dual-purpose animals that are highly suitable for range conditions (Snowder *et al*., 1997b).

Merino sheep first came to Australia in 1797 from the Dutch Cape Colony in South Africa. Before being exported to South Africa the Merino sheep were produced primarily in Spain and most likely Asia or North Africa prior to the Spanish ownership. By the mid-1800’s, Australian sheep breeders began developing different strains of Merino sheep. The South Australian Merino was adapted to survive the arid weather conditions in South Australia. They are known for their strong wool, which is coarser in its fiber diameter (Cottle, 1991). The Peppin strain of Australian Merino sheep originated in New South Wales. The wool produced by Peppin Merinos falls in the mid-range of fiber diameter (20-23µm). Peppin Merinos were adapted to flourish in the drier inland regions of Australia. The Saxon Merino strain was adapted to thrive in the high rainfall areas and is known for its small fiber diameter typically ranging from 17-20 µm.

Despite the fact that both Australian Merinos and Texas Rambouillets originally came from Spain, hundreds of years of separate breeding programs have led both breeds to focus on different traits. Some Australian breeders have focused much time and effort in producing some of the finest wool clip in the world. Although, there have been extensive reviews conducted over genetic parameters in sheep, the heritability of a given trait can vary widely in different populations and environments (Wuliji *et al*., 2001). For instance, previous studies conducted with Merino and Rambouillet sheep populations the heritability of individual weaning weight ranged from 9% to 20% (Bromley *et al*., 2001). Studies conducted in Australia have found high maternal genetic and litter correlations between clean fleece weight and grease fleece weight with moderately high correlation to fiber diameter. In a study conducted in New Zealand, genetic correlations were found to be high among the live weights but low to moderate among fleece weight and wool characteristics. Heritability estimates of fiber diameter, fiber diameter variation and staple length were found to be very high. It was noted in that same study that with age, the average fiber diameter increases and the strength of the fiber often decreases due to increased variation in the fiber diameter along the fibers making the fibers less likely to withstand tear force (Wuliji *et al*., 2001).

In addition to the fleece characteristics, a high genetic correlation was found between weaning weight and weights at older ages (Safari *et al*., 2007). An analysis of an Australian Merino population over several decades showed improvements in the genetic levels of wool production traits are possible using currently available bloodlines (Mortimer *et al*., 1989). However, in the United States, producers have focused their efforts more on prolific, dual-purpose sheep capable of producing an adequate amount of relatively fine (20-24µm) wool and lambs with excellent meat and muscling attributes. Unfortunately, when Merino sires were selected based solely on improving wool characteristics, their use resulted in decreased prolificacy and total litter weight weaned per ewe in U.S. flocks (Snowder *et al*., 1997a). But it was also found in that same study that fleece weight, staple length and yield were significantly increased through the crossbreeding of Australian Merinos on U.S. fine-wool sheep as well as a decrease in average fiber diameter of 0.5µm (Snowder *et al*., 1997b). An earlier study conducted to analyze the differences in carcass traits of U.S. breeds and both Australian fine- and strong-wool Merino sheep found that the increased wool production would come at the expense of feed conversion rate and carcass leanness (Sakul *et al*., 1993). However, no major antagonisms have been found in studies on Australian Merinos between wool and meat traits (Safari *et al*., 2007). The selection of Merino sires should account for carcass traits of offspring to avoid negative effects on carcass traits. Because fleece traits, such as average fiber diameter, yield, and staple length are relatively highly heritable traits and there are differences between the U.S. and Australian fine wool populations, it is suggested that potential gains may be realized by mating selected Australian Merino rams to U.S. Rambouillet ewes.

Australian Merinos are known worldwide for exceptional wool quality that is suitable for high-fashion apparel and textiles (Simpson *et al*., 2002). Historically, Merino wool has been sought after by high-end fashion labels due to its soft handle, impeccable drape, and the simplicity that comes with working with wool fibers. However, in reality these smaller fiber diameter wools are produced by an array of sheep of various breeds and crosses. But, the Australians have branded Merino wool due to the higher quality of the wool and because they have much larger volumes of small fiber diameter wool. So, they use the breed name as though it was a brand name to ultimately gain consumer recognition. In addition, the genetic improvements made by the Australians, including decreased fiber diameter wool and cleaner, higher yielding fleeces make Australian wool more valuable in the commercial market as it is preferred by the processing industry compared to U.S. produced wool.

Wool is a specialty fiber due to its exceptional attributes and because it only accounts for approximately 1.3% of the world fiber market. New advancements in research and development are finding wool is suitable and often more desirable than synthetics in active wear garments (Simpson *et al*., 2002). The latest developments in wool textiles have led to the creation of lighter-weight and softer fabrics made with smaller diameter wool that are geared towards active and casual wear. These textiles exhibit the natural moisture absorption attributes including that a wool fiber can absorb up to 35% of its own weight in water at a high humidity before feeling wet (Collie *et al*., 1998). Small fiber diameter wool may be used to produce high-quality sports apparel, which has the ability to actively manage heat and moisture flows from the body under a variety of conditions. It also suppresses odors, has high abrasion resistance, is very durable, and delivers the highest levels of comfort and performance (Collie *et al*., 1998). Knitted fabrics are the most common fabric structure for base layer active wear because the uneven surface of a knitted textile actually feels more comfortable next to the skin than woven fabrics of similar fiber compositions (Troynikov *et al*., 2011). Wool is an exceptionally resilient fiber making it an ideal fiber for use in knit fabrics without the assistance of elastic for stretch.

Consumer studies completed in the United States show consumers' preference for purchasing garments made in their home country (Hustvedt *et al*., 2013). One major setback in trying to build this demand domestically is the relative scarcity of wool < 20 µm in the United States wool clip (R. Pope, PMCI, Mertzon, TX, USA, personal communication). This explains why domestic (and foreign manufacturers) often turn to larger wool producing countries such as Australia or New Zealand for the smaller fiber diameter wools. In addition to the lower volumes and inadequately prepared fine wools produced in the United States, there are also implications affecting domestic manufacturing industry due to the outsourcing of apparel production jobs to countries with lower wages. Although there has been a slight resurgence of apparel manufacturing jobs within the United States, ongoing trade agreements continue to challenge the future of that industry here in the United States.

Another issue historically facing consumers when deciding whether to purchase wool garments was the added time and expense of dry-cleaning those garments. However, advancements in technology have led wool to be treated with chemicals to allow garments to be washed without causing shrinkage (Simpson *et al*., 2002). The process is known as the chlorine-Hercosett process, but is more commonly referred to as the “superwash” process. The superwash process includes equipment that immerses the wool fibers into a mild chlorine solution after which the fibers are rinsed, immersed into a polymer resin and then dried and cured. The exposure to the chlorine removes the protective exterior layer from the wool by smoothing out the protruding scales on the surface of the fibers. Additionally, the application of the polymer resin further increases the smoothness of the fibers, which decreases the felting shrinkage, caused by interlocking of wool-fiber’s scales. The resulting fibers are highly suitable for use in next-to-skin textiles that will not shrink when washed using in-home laundry machines allowing these garments to meet Total Easy Care standards set for wool products (Simpson *et al*., 2002).

Many consumers tend to believe wool is only preferred in colder climates during the winter. However, studies show wool is also highly suitable for active-wear apparel of all kinds and for all seasons (Collie *et al*., 1998). Small fiber diameter wools can be used to produce high-quality sports apparel, which delivers the highest levels of comfort and performance (Holcombe *et al*, 2009). Prior to the 1950’s and the invention of mass-produced synthetic fibers, wool was used in a wide variety of active wear apparel. The rise of synthetics in active wear apparel and the differentiation of products companies have made based on specific activities has allowed for the marketplace to be dominated by synthetics due to the lower cost and the readily available high volumes of raw fiber ready for manufacturing. However, recently there has been increased awareness of health benefits to staying active as well as a shift especially in countries such as the United States to more casual dress styles on a day-to-day basis. Wool apparel has also undergone so much scrutiny especially by competing fiber manufacturers that many believe it to have many negative attributes that may only exist with coarser wools or not even at all. Still, one of the major negative issues for consumers of knitwear composed of wool is the prickle or itch sensation that over 50% of people in key markets associate with wool (McGregor *et al*., 2015). At this point, there are no other known fibers, man-made or natural, that can match the versatility that wool offers to not only the active wear market but many others even outside of the apparel industry. The wool fiber is an excellent thermal insulator, even when wet and has the highest moisture regain out of all fibers at a given temperature and relative humidity (Troynikov *et al*., 2011).

In hot climates, clothing acts as a barrier to thermal balance by inhibiting evaporative and convective cooling making the fabric, clothing construction and fit critical influencers of the amount of sweat absorbed from the skin and transported through the clothing to the external environment (Davis *et al*., 2013). In these warm environments or during strenuous exercise, a wool garment close to the skin actively transfers moisture vapor molecules away from the body making the wearer less clammy. Unlike wool, synthetics do not have the ability to absorb moisture, so the moisture sits in miniature droplets on the fibers' surface.

Polyester is the single most commonly used fiber in active wear (Troynikov *et al*., 2011). However, polyester is a hydrophobic, oil-based synthetic fiber, which must be chemically treated to have a hydrophilic outer layer to make it suitable for use in active wear. Wool not only provides a garment with better insulation but also allows for the garment to be breathable while locking away odor molecules to keep the garment smelling fresh despite strenuous activity. These moisture retention characteristics also make wool less prone to the buildup of static electric charge than synthetic fibers making garments that are more comfortable to the wearer.

Maintaining thermal balance in a hot environment is not only critical to preserving life and reducing heat ailments; it is also essential in order to prevent decrements in athletic performance (Davis *et al*., 2013). There are other key factors that can disrupt thermal balance including: clothing, exercise intensity, radiation, humidity, and ambient temperature. Despite these threats to maintaining thermal balance, the human body is exceptionally adaptive in managing extreme temperatures with the correct clothing. Tokura *et al*., (1987) compared the effects of wearing 100 % polyester and 100 % wool during 45 min of seated rest, 10 min on a cycle ergometer at 32 W, and then 45 min of recovery at 34 deg C and in 63 % relative humidity. The clothing surface temperature was significantly higher at rest when using polyester. Core temperature and heat storage were significantly higher when polyester was used rather than wool during exercise and recovery. After analyzing several studies, Davis *et al*., (2013) found synthetic fabrics seem to offer no thermal balance advantage over natural fabrics during exercise.

In addition to thermoregulation properties, comfort is another key factor consumers consider when purchasing clothing, especially those intended for exercising. However, the comfort of clothing relates to a broad number of factors and can be very challenging to define. Comfort also differs between individuals. Previous studies have identified that the important aspects of garment comfort can be grouped into four major areas: thermos-physiological components, sensorial comfort, ease of body movement and aesthetic appeal (McGregor *et al*., 2015). When focusing on the sensorial comfort, which is often called into question by consumers regarding wool, fabric-evoked prickle is one of the most commonly encountered and disliked sensorial sensations (Garnsworthy *et al*., 1988).

In an attempt to improve consumers' view of knitted wool textiles and offer manufacturers a way to assess wool fabric comfort, the Wool ComfortMeter instrument was developed to establish a rapid, instrumental approach for predicting a wearer's perception of fabric-evoked prickle (McGregor *et al*., 2015). The Wool ComfortMeter uses a measurement wire mounted in a recording head, which scans the surface of the fabric, interacting with fibers protruding from the fabric surface (Ramsay *et al*., 2012). The results produced are sensitive to variations in the spatial density of stiff fiber ends protruding from the fabric surface such that coarser fibers and more prickly fabrics result in higher Wool ComfortMeter measurements which indicate less-desirable fabrics (McGregor *et al*., 2015). Through the objective measurement of knitted wool fabrics, manufacturers can ensure the comfort of a fabric before it is manufactured into a garment.

Along with the Wool ComfortMeter, the Wool HandleMeter was also developed to measure the handle parameters of knitted single jersey fabric (McGregor *et al*., 2015). According to McGregor, this device is based on a test where a circular fabric sample is pulled or pushed through a circular orifice to determine a relative hand value, drape index, and wrinkle recovery rate. Together the Wool ComfortMeter and Wool HandleMeter provide objective measurements of two important aspects of concern to consumers purchasing lightweight jersey wool knitwear (McGregor *et al*., 2015).

MATERIALS & METHODS

General Experimental Design

A flock of 300 commercial Rambouillet (R) ewes ranging from 2 to 7 years old with an average fiber diameter of 21.3 µm was assembled and maintained by Texas A&M AgriLife Research personnel on a ranch, known as the Martin Ranch near Menard in west-central Texas. Genetic data from ram test data records and Australian sheep databases were analyzed to select fine-wool sires with great potential for decreasing fiber diameter and increasing fleece weight when bred to the ewes selected for this study. The Australian Merino was selected as the breed of choice to crossbreed with the Texas Rambouillet ewes because of the high-quality, small fiber diameter wool that they have been bred to produce. Additionally, the databases available in Australia allowed for simplistic comparison of many different sires from across the various regions of Australia. The sires selected for this study were those that possessed not only the fiber and fleece characteristics desired but also were of similar size and stature as the traditional Texas Rambouillet sires. Additional considerations were made to select sires free from wrinkles and with desirable body weight in an effort to keep or improve the current size and conformation of the Rambouillet. Two databases were identified and used to compare Australia's top sires based on genetic merit of the traits measured. Semen was available from many of the rams included in these databases. Through the use of the databases, as well as other resources in Australia, semen was purchased from 5 Merino (M) rams, and was used in 3 consecutive years to produce offspring from Rambouillet ewes. The semen was purchased from Hyfield, Leahcim, Keri-Keri, and Wallaloo Park stud flocks in Australia. In the third year, three additional U.S. Merino sires were purchased from the University of Nevada-Reno from the Merino flock established by Dr. Hudson Glimp at the Rafter 7 Ranch. These sires were selected based on their superiority for fiber fineness and wool production and were comparable in body size and weight to the Texas Rambouillet. In addition, using the Texas Agriculture Experiment Station Sire Summary of Ram Test Performance data, eleven Rambouillet rams were selected to be borrowed and/or purchased that were within the top 30% of rams on test and were also used over the three-year timeline. Most belonged to and had been retained as studs by the Texas Rambouillet Superior Genetics group. Two other rams were made available from the Angelo State University flock and from the R. Q. Landers Ranch. Those rams too were superior for fiber fineness and wool production. Table 1 shows the number and breed of the rams used in this study and the number of ewes they were exposed to each year. All procedures involving animals were approved by the Texas A&M University Institutional Agricultural Animal Care and Use Committee under protocol 2007-1.

Table 1: Breeding Summary per Year

	2007		2009		2010	
Sire Type	Number of Rams	Number of Ewes Exposed	Number of Rams	Number of Ewes Exposed	Number of Rams	Number of Ewes Exposed
Australian Merino	4	198	3	219	5	69
US Merino	0	-	0	-	4	114
Rambouillet	4	117	4	129	6	164

Description of Traits

Over the next 3 years, the performance was recorded for body weight, lamb production, and wool production on the resulting R and F_1 M X R lambs. The first year lambs were born in the fall and raised under range conditions and paternity was confirmed by DNA analysis of blood. To avoid predation losses and the necessity of DNA testing, ewes were shed-lambed in subsequent years. Additionally, ewes were bred to lamb in the spring in later years. All ram lambs were managed in a single group and all remained intact. Lambs were weighed before, at, and after weaning and all sheep were weighed after shearing. The lambs were approximately 120 to 230 days of age at weaning depending on the sex and the year they were born. Ewes were also weighed at the time of breeding. Table 2 shows the number of lambs born by sex, year, and breed of sire. Table 3 shows the number of lambs weaned and mean weaning weights by sex, year and breed of sire and.

Table 2: Number of Animals Born into the Program by Sex and Breed of Sire

	Male		Female	
Year	MR[a]	R[b]	MR[a]	R[b]
2007	22	24	25	20
2009	54	50	42	44
2010	73	73	74	88
All Years	149	147	141	152

[a] MR= Merino x Rambouillet, [b] R= Rambouillet

Table 3: Weaning Weight data

	Male				Female			
	MR[a]		R[b]		MR[a]		R[b]	
Year	N	Mean kg	N	Mean kg	N	Mean kg	N	Mean kg
2007	22	29.28	24	30.69	25	26.04	20	27.47
2009	48	36.59	46	35.65	33	29.32	30	30.43
2010	50	26.58	51	27.95	56	24.83	65	27.97
All Years	120	31.08	121	31.42	114	26.49	115	28.52

[a] MR= Merino x Rambouillet, [b] R= Rambouillet

The fleece records include grease fleece weight, average fiber diameter, standard deviation average fiber diameter, coefficient of variation average fiber diameter, staple length, comfort factor, curvature, standard deviation curvature. Shearing took place in April and fleeces were individually bagged and labeled at shearing and objective measurements of fleece and fiber traits were conducted thereafter. Each greasy fleece was weighed and recorded. Grease fleece weights were adjusted to a 365-d growth period. The fleeces were subsampled for staple length. Ten staples were removed from random positions in each fleece and measured using a standard method (American Society for Testing and Materials [ASTM, 2009b]) to calculate mean and standard deviation of staple length. Staple length measurements were also adjusted to a 365-d growth period. Subsequently, fleeces were subsampled again using a mechanical coring device (Johnson and Larsen, 1978). Approximately thirty-two 1.27 cm cores (total weight, > 50 g) were removed from each fleece. These core samples were used for the measurement of clean yield (estimated clean wool fibers present; ASTM, 2009a). Clean samples from the yield test were minicored to produce snippets (short pieces of fiber, approximately 2 mm in length). These snippets (approximately 5,000 per fleece) were measured for mean fiber diameter and SD using an optical fiber diameter analyzer (IWTO, 2013). The final two years of fleece evaluation (2013 and 2014) the ewes were sheared in January. Fleeces were collected, weighed and side samples were collected from each fleece. The side samples were analyzed for fiber diameter and staple length measurements using an optical fiber diameter analyzer. . Table 4 shows the number of fleeces collected and analyzed throughout the study. Tables 5 and 6 show the ram and ewe average fleece and fiber characteristics by year of the study.

Table 4: Number of Fleece Records by Age, Sex and Breed of Sire

	Male		Female	
Age	MR[a]	R[b]	MR[a]	R[b]
Yearling	113	97	112	107
2-Year Old	65	63	100	94
3-Year Old	18	21	82	79
4-Year Old	-	-	69	23
5-Year Old	-	-	22	9
6-Year Old	-	-	10	-
All Years	196	181	395	312

[a] MR= Merino x Rambouillet, [b] R= Rambouillet

Table 5: Ram Fleece Data Records by Year

	GFW kg		LSY %		AFD µm		CF %		SL cm		AFC deg/mm	
Year	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean
2009	42	4.46	42	59.13	42	17.94	42	99.71	42	11.60	42	91.62
2010	136	3.60	136	61.75	136	18.69	136	99.50	134	11.15	136	88.99
2011	199	3.90	199	62.13	199	18.38	195	99.49	199	9.59	195	91.73
All Years	377	3.84	377	61.66	377	18.45	373	99.52	375	10.37	373	90.72

Table 6: Ewe Fleece Data Records by Year

	GFW kg		LSY %		AFD µm		CF %		SL cm		AFC deg/mm	
Year	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean
2009	43	4.03	43	58.19	43	18.51	43	99.55	43	11.87	43	90.59
2010	106	3.13	106	60.50	106	18.41	106	99.53	105	10.69	106	89.33
2011	202	3.64	202	48.06	201	18.29	201	99.51	204	8.45	203	88.01
2012	148	3.60	148	49.40	148	19.22	148	99.54	147	9.54	148	90.78
2013	141	3.62	-	-	142	20.49	142	98.91	141	7.32	142	78.50
2014	62	4.25	-	-	64	19.50	64	99.50	64	8.68	64	73.96
All Years	702	3.63	499	51.97	704	19.07	704	99.40	704	9.01	706	85.76

Statistical Analysis

Data collected in this study were analyzed using PROC MIXED of SAS (SAS Inst. Inc., Cary, NC). The statistical model used for weaning weights on both the ewes and the rams born into the study included fixed effects of genotype (R vs. MR), year of birth, type of birth (single vs. twin), a linear covariate of weaning age in days, and a random effect of sire within genotype. The statistical model used for the fleece and fiber traits of both the ewes and rams born into the study included fixed effects for genotype, age, and year the fleece was shorn. It also included a random effect for sire within genotype and animal within genotype and sire. Initially, the model also included an interaction of genotype by age, however, based on the results there were no biological effects discovered so this interaction was left out of the final model.

Active Wear Apparel Manufacturing

In addition to the live animal portion of this project, a comparison of garments manufactured of 100 % American wool that mimics the diameter of the wool produced by both the Rambouillet and Merino X Rambouillet offspring throughout all years of this study was conducted. The wool used was American grown wool and was purchased as superwashed wool top from Chargeurs Wool in Jamestown, SC. The wool top was then shipped to Kent Wool in Pickens, SC, a company specializing in spinning yarn from wool, for yarn manufacturing. Based on the diameter of the fiber to be spun 1/39 worsted count yarn was spun at Kent Wool. This yarn size was selected as it is highly suitable and commonly used in light-weight knit garments. Following yarn production, the yarn was sent to North Carolina State University's Textile Extension Lab in Raleigh, NC to be knitted into fabric. Both diameter wools were dyed in the same dye lot. The fabric was piece dyed and finished at Alamac American Knits in Lumberton, NC. Two fabrics were made out of each type of wool, a single jersey knit weighing approximately 135 g/m^2 and an interlock knit weighing approximately 240 g/m^2. The single jersey knit was used in a running t-shirt shown in Figure 1 and running shorts shown in Figure 2. The double knit fabric was used to create a mid-layer pullover shown in Figure 3. Once the fabrication process was complete the fabric was sent to Carolina Apparel Goods in Wadesboro, NC to be manufactured into the prototype garments for testing.

Figure 1: T-Shirt Technical Sketch

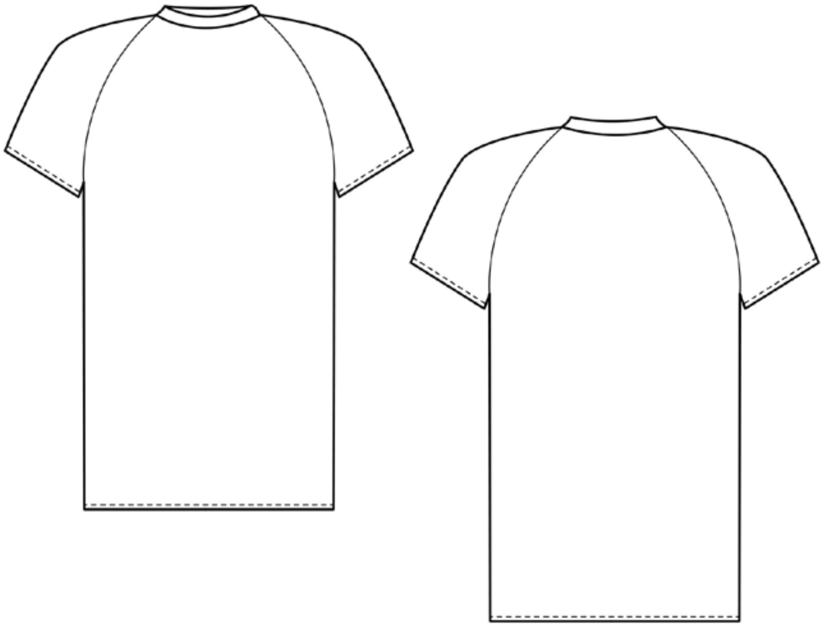


Figure 2: Shorts Technical Sketch

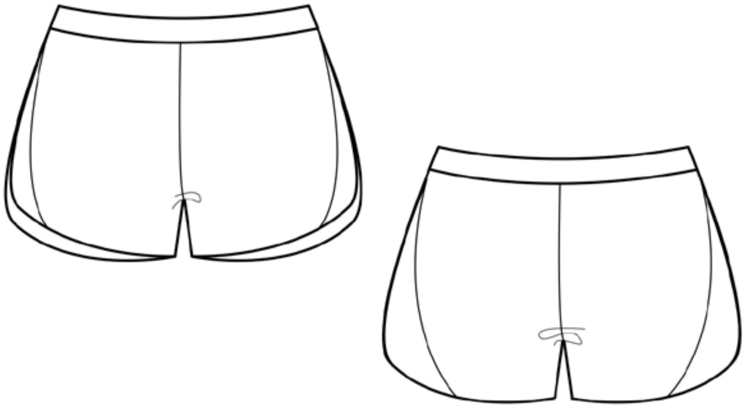
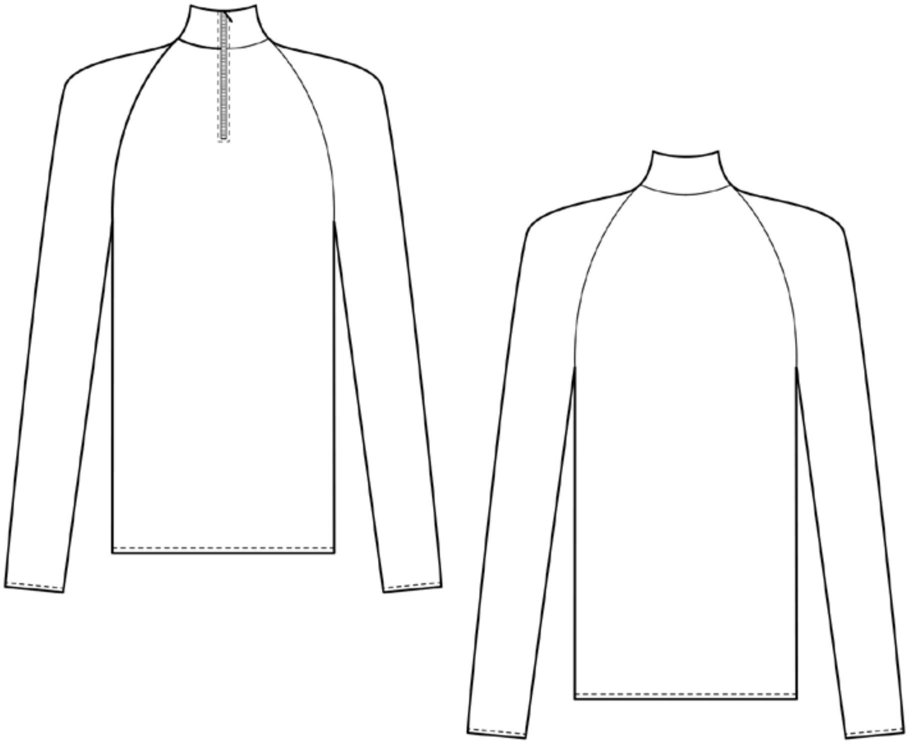


Figure 3: ¼ Zip Pullover Technical Sketch



Tests were performed throughout all stages of manufacturing to determine key characteristics of varying fiber diameter wools and how it ultimately affects the performance of the end garment. The tests were also used to compare the performance characteristics of the fabrics and garments produced in this study to other fabrics and garments produced from other fibers based on other research studies. The majority of the tests occurred at the fabric and final garment stages. Fabrics tests via the Wool ComfortMeter and Wool HandleMeter were performed by the Australian Wool Testing Authority in Melbourne, Australia and all other tests were performed by North Carolina State University's Textile Testing laboratories in Raleigh, NC.

Fabric Tests

The Wool ComfortMeter (WCM) and Wool HandleMeter (WHM) are two new testing devices developed in Australia specifically for testing wool knit fabrics. The perceived comfort of the fabrics was tested using International Wool Textile Organisation (IWTO) Draft Test Method (DTM) Standard 66, for skin comfort of finished wool fabrics and garments (IWTO, 2014a). The Wool ComfortMeter counts the number of protruding fibers from a fabric sample. More protruding fibers indicates a less comfortable fabric. Five fabric samples were tested and averaged to get a single value for the fabric. The lower the value, the better the garment is for next to skin applications. The WCM was designed to test the back of fabric samples and interlock knits do not have a back. Thus, the results of the interlock knit fabrics were only used as a comparison between themselves. The indexes developed to analyse the comfort of knit wool fabrics are listed in Table 7.

Table 7: Wool ComfortMeter Indexes

% of consumer acceptance for comfort level	Comfort Level (WCM)	
	1-Everyday Fashions	2- Active Wear
90	<450	<250
80	450-510	250-320
70	510-600	320-400
60	600-660	400-480
50	660-730	480-550
40	730-810	550-620

The WHM was only developed for single jersey knit fabrics and there is currently no calibration for interlock knit fabrics. Consequently, the results were only used as a comparison between like fabrics produced in this study. The handle of the fabrics were tested via IWTO DTM Standard 67, a draft test method for objective handle evaluation of fine lightweight knitted fabrics by a wool handlemeter (IWTO, 2014b). The WHM measures seven core attributes of handle: smoothness, softness, warm feel, dry feel, hairiness, tightness and perceived weight as well as an overall handle index. For each WHM parameter, the predicted value varies between 1 and 10, with 1 associated with the first term for the parameter and 10 being associated with the last term for the parameter (McGregor *et al.*, 2015). Table 8 displays the scale for each wool HandleMeter parameter.

Table 8: Wool HandleMeter Parameters (McGregor *et al.*, 2015)

Parameter	Descriptor and Definition of Scale
Clean/Hairy	Surface property: 1, extremely clean; 10, brushed/raised (very hairy)
Greasy/Dry	Surface property: 1, excessive finish (greasy); 10, extremely dry
Rough/Smooth	Surface property: 1, very rough; 10, extremely smooth
Hard/Soft	Flexural property: 1, extremely hard; 10, extremely soft
Loose/Tight	Flexural property: 1, extremely loose; 10, extremely tight
Cool/Warm	Perceived temperature: 1, extremely cool; 10, extremely warm
Light/Heavy	Bulk property: 1, extremely light; 10, extremely heavy
Overall Handle	Overall fabric handle: 1, poor; 10, excellent

Abrasion resistance of the fabrics was tested using ASTM (American Society for Testing and Materials) D 4966, standard test method for abrasion resistance of textile fabrics. This method covers the determination of the abrasion resistance of textile fabrics using the Martindale abrasion tester (ASTM, 2010a). The fabrics were evaluated via Option 1 – The end point was reached on a knitted fabric when a hole appears. Pilling resistance was determined using the Martindale abrasion tester via ASTM D 4970, the standard test method for pilling resistance and other related surface changes of textile fabrics (ASTM, 2010b). This test was performed to simulate normal wear of a fabric although many factors can affect pilling including: type of fiber or blends, fiber dimensions, yarn and fabric construction and fabric finishing treatments. Burst strength was evaluated through ASTM D 3786, the standard test method for bursting strength of textile fabrics—diaphragm bursting strength tester method (ASTM, 2009c). This method describes the measurement of the resistance of textile fabrics to bursting using a hydraulic or pneumatic diaphragm bursting tester.

The dimensional change of the fabrics was tested through AATCC (American Association of Textile Chemists and Colorists) test method 135, the standard method to determine dimensional changes of fabrics after home laundering (AATCC, 2014). The dimensional change was evaluated following the washing of the fabric in the normal/cotton sturdy machine on the warm setting to imitate home washing machines and procedures commonly used by consumers. The fabric was also line dried. Three additional washing techniques were conducted on both the single and interlock fabrics from the 19.9 µm fabrics to analyze any changes based on laundering settings. The additional washing techniques involved washing on a normal/cotton sturdy setting. One set was washed in cold water and line dried, another set of samples was washed in cold water and tumble dried, and the last set of samples was washed in warm water and tumble dried. These additional tests indicated how different washing methods could potentially affect the fabrics. Colorfastness to crocking was tested via AATCC test method 8, the standard method to detect colorfastness to crocking: crockmeter method (AATCC, 2013a). This test method determines the amount of color transferred to other surfaces through rubbing. Colorfastness to perspiration was tested via AATCC test method 15, colorfastness to perspiration (AATCC, 2013b). This test was used to determine the effects of acid perspiration on colored textiles.

Final Garment Tests

A sweating manikin was used to determine the insulation and breathability of garment systems through ASTM F 1291, the standard method for measuring the thermal insulation of clothing using a heated manikin (ASTM, 2010c) and ASTM F 2370, the standard test method for measuring the evaporative resistance of clothing using a sweating manikin (ASTM, 2010d). Tests for thermal resistance occurred in non-isothermal conditions; tests for evaporative resistance were carried out under isothermal conditions. The testing conditions used are shown in Table 9. Three repetitions were completed for each garment configuration, as specified by these standards.

Table 9: Manikin Testing Conditions

	Thermal Resistance	Evaporative Resistance
Air Temperature (°C)	20	35
Relative Humidity (%)	50	40
Air Speed (m/s)	0.4	0.4
Skin Temperature (°C)	35	35

Advanced "Newton" type sweating manikin systems are used to evaluate whole garments systems (or components of garment systems) for heat and moisture management related to garment insulation and breathability. The manikin has several features which work together to evaluate clothing comfort and/or heat stress. By measuring these values on a human form, garments are able to be evaluated as they would be worn. Effects of fit, garment construction and design are thus accounted for. Thus, manikin heat loss measurements are much better approximations for realistic human heat loss than measurements made on the material system alone. In addition, the manikin is articulated and has a movement system designed to emulate the pumping action created by walking.

RESULTS AND DISCUSSION

Live-Animal Results

The least squares means of the weaning weights by sex and genotype are shown in Table 10.

Table 10: Least Square Means of Weaning Weight by Sex and Genotype

	Genotype		
Sex	MR[a]	R[b]	Pr > |t|
Rams	30.77±1.64	30.94±1.63	0.86
Ewes	27.38±1.20	29.11±1.17	0.05

[a] MR= Merino x Rambouillet, [b] R= Rambouillet

The lambs ranged from 120 to 230 days of age at weaning depending on the sex and the year they were born. However, weights were adjusted to 120 days of age for statistical analysis. There was a greater difference between weaning weights observed in the ewes (p = 0.05) than the rams (p = 0.86) between the two genotypes. The lack of differences between the two genotypes may be a result of the selections made on the Merino sires that were selected based on size and body weight as well as for superior fiber characteristics. In both breeds on average the males weighed more than the females at weaning. However, the difference between the average weaning weights between the MR and R rams born into the study was not significant. The 1.7 kg difference between MR and R ewes for weaning weights was significant (P=0.05).

In a study conducted in Australia analyzing three different populations of three different strains of Australian Merino rams, average body weights of 24.6 kg at 87 d of age (Mortimer *et al*., 1989) were reported. A subset of the MR and R rams born from the current study weighed at approximately 68 d of age and averaged smaller body weights at 18.8 kg however, the average daily gain from birth to 68 d of age was nearly identical between the two studies. Also when comparing the average weights of the MR versus the R of that same subset of rams at approximately 68 d of age the MR averaged slightly greater body weights than the R rams by 0.1 kg. Snowder *et al*. (1997b) combined both the ewes and the rams as lambs for body weight analysis and found greater average weights of approximately 30 kg at approximately 110 d of age than a subset of 2010 born rams which were weighed at approximately 140 d of age and averaged only 27 kg. However, both studies found Rambouillet-sired lambs averaged greater body weights than Merino-sired lambs. In another study that analyzed traits of Rambouillet sheep in the United States over nearly 50 years, Hanford found slightly greater body weights of 32.3 kg at approximately 120 d of age compared to the rams in this study which averaged 27 kg at 140 d of age (Hanford *et al*., 2005.

Another 15-year study conducted solely on a Merino stud flock in Uruguay found lower average body weight of 23 kg at approximately 130 d of age compared to the subset of sheep from the present study that averaged 27 kg at 140 d of age (Ciappesoni *et al*., 2013). In a study conducted in South Africa designed to improve average fiber diameter that analyzed a fine-wool and a control flock for ten years for both body weight and wool traits, the researchers observed significantly different average birth weights of the offspring from the two flocks but both flocks had identical weaning weights which was very similar to what was observed with the ram lambs in this study (Oliver *et al*., 2007).

The least squares means for the fleece and fiber data for both the ewes and the rams born into the study are presented in Table 11 and Table 12, respectively.

Table 11: Least Squares Means for the Wool Characteristics of the Ewes Sired by Merino and Rambouillet Sires

	Genotype		
Dependent Variable	MR[a]	R[b]	Pr >|t|
Adjusted Grease Fleece Weight (kg)	3.72±0.10	3.52±0.10	0.06
Lab-Scoured Yield (%)	55.29±0.61	52.92±0.61	<0.01
Adjusted Clean Fleece Weight (kg)	1.97±0.05	1.83±0.05	0.01
Average Fiber Diameter (µm)	18.95±0.22	19.35±0.22	0.10
Standard Deviation of Average Fiber Diameter (µm)	3.46±0.07	3.53±0.07	0.36
Coefficient of Variation of Average Fiber Diameter (%)	18.35±0.29	18.23±0.30	0.72
Comfort Factor (%)	99.50±0.10	99.31±0.10	0.11
Adjusted Staple Length (cm)	9.29±0.22	8.62±0.22	0.01
Standard Deviation of Adjusted Staple Length (cm)	0.87±0.03	0.82±0.03	0.10
Average Fiber Curvature (deg/mm)	81.81±2.08	91.41±2.07	<0.01
Standard Deviation of Average Fiber Curvature (deg/mm)	55.38±1.17	60.50±1.16	<0.01
Coefficient of Variation of Average Fiber Curvature (%)	67.80±0.46	66.19±0.48	<0.01

[a] MR= Merino x Rambouillet, [b] R= Rambouillet

Table 12: Least Square Means for the Wool Characteristics of the Rams Sired by Merino and Rambouillet Sires

	Genotype		
Dependent Variable	MR[a]	R[b]	Pr > |t|
Adjusted Grease Fleece Weight (kg)	4.18±0.08	3.86±0.08	<0.01
Lab-Scoured Yield (%)	63.90±0.83	60.01±0.76	<0.01
Adjusted Clean Fleece Weight (kg)	2.68±0.06	2.35±0.06	<0.01
Average Fiber Diameter (µm)	18.75±0.22	19.49±0.21	<0.01
Standard Deviation of Average Fiber Diameter (µm)	3.90±0.07	4.11±0.07	0.01
Coefficient of Variation of Average Fiber Diameter (%)	20.61±0.44	21.01±0.40	0.40
Comfort Factor (%)	99.53±0.06	99.33±0.06	0.01
Adjusted Staple Length (cm)	9.90±0.25	9.42±0.23	0.10
Standard Deviation of Adjusted Staple Length (cm)	0.96±0.03	0.90±0.03	0.08
Average Fiber Curvature (deg/mm)	85.52±1.92	96.31±1.78	<0.01
Standard Deviation of Average Fiber Curvature (deg/mm)	56.28±0.92	62.49±0.86	<0.01
Coefficient of Variation of Average Fiber Curvature (%)	66.12±0.62	65.01±0.57	0.10

[a] MR= Merino x Rambouillet, [b] R= Rambouillet

Both the MR ewes and rams grew heavier, cleaner, finer and longer stapled fleeces than their R counterparts. The MR ewes averaged 0.2 kg greater grease fleece weights and nearly 3% higher yields which led to higher clean fleece weights. The MR ewes also averaged 0.67 cm longer staple lengths and their average fiber diameter was about 0.4 µm finer than the R ewes over the course of the study. The MR rams followed the same trend as the ewes. However, the differences between the genotypes were larger for the rams than the ewes in this study. The MR rams averaged 0.3 kg heavier grease fleece weights and nearly 4% higher yields. They also averaged 0.75 µm finer fleeces and 0.5 cm longer staple lengths compared to their R counterparts.

Although, the Merino ewes consistently grew more, finer, and longer wool than the Rambouillet ewes, Snowder *et al.* (1997a) reported larger differences between the Australian Merino F1 crosses and the Rambouillet wool characteristics than were found in the present study. Snowder found that the fine-wool Merino ewes had greater variation of grease fleece weights and yields that subsequently led to greater variation of final clean fleece weights when compared to their Rambouillet counterparts (Snowder *et al.*, 1997a). In that study the fine-wool Merino ewes averaged 0.3 kg heavier grease fleece weights and 4.6 % greater yields which resulted in 0.4 kg greater clean fleece weights.

Another similar study was conducted over both Rambouillet and Merino Rambouillet F1 crosses analyzing the wool traits of a smaller flock of just over 100 ewes over a two year time period. In this study the ewes had greater clean fleece weights than the ewes in the present study at 2.55 kg on the Rambouillet ewes and 3.50 kg on the Merino Rambouillet F1 cross ewes (Aimone *et al*., 1999). However, the yield was determined based on the yield from a side sample rather than a core sample of the entire fleeces, which could explain some of the differences in the clean fleece weights between the two studies. Fleece weights in the present study (Tables 11 and 12) were lower than those reported in Rambouillet sheep in the US by Bromley *et al*. (2001) of 5.1 kg and Hanford *et al*. (2005) of 4.7 kg. The lower fleece weights are likely a result of nutrition differences which were due to pasture conditions during a period of drought in Texas in 2011 and 2012.

In a study conducted in Australia comparing strains of Merino ewes at multiple locations across the country, greater grease fleece weights of 4.5 kg and yields around 69% which subsequently led to greater clean fleece weights of just over 3 kg were reported (Mortimer *et al*., 1989). In addition, Oliver reported grease fleece weights of the offspring of both Merino lines averaging over 4 kg and yields averaging 67% (Oliver *et al*., 2007). Also, the study conducted in Uruguay reported average grease fleece weights of 3.0 kg and clean fleece weights of 2.3 kg (Ciappesoni *et al*., 2013). Although the average yield was not recorded in their study and the sample size was slightly smaller for the clean fleece weights recorded compared to the total number of grease fleece weights, the fleeces still would have averaged at least a 70% yield. These differences can largely be attributed to these being full-blood Merino but also and perhaps primarily to the differences in environment that directly affect all of these traits rather significantly.

Grease fleece weight and clean fleece weight reached its maximum at four years of age and then began to decline in Australian Merino ewes (Safari *et al*., 2007). In that same study the average maximum yield occurred at age three and then began to gradually decline (Safari *et al*., 2007). Mortimer found that year was a significant source of variation for differing wool traits over a several year analysis, but age effects on wool production were still apparent (Mortimer *et al*., 1989).

Aimone *et al.* (1999) found both the Rambouillet and the Merino Rambouillet F1 crosses had smaller fiber diameters, 18.21 μm and 17.58 μm respectively, than were observed in the present study. They also found lower coefficients of variation of the fiber diameter as expected with the smaller micron fleeces (Aimone *et al.*, 1999). Mortimer's estimate of the average fiber diameter of Merino ewes of several strains was 20.38 μm, but this again can be attributed to the inclusion of differing strains of Merino ewes with medium wool (Mortimer *et al*., 1989). The difference in fiber diameter between the two fine wool and the control flocks in the South African study was one of the most significant differences out of all wool traits observed between the two flocks in Oliver's study. The fine wool line averaged 18.0 μm and the control line averaged 19.6 μm (Oliver *et al*., 2007). However, decreasing fiber diameter was the main goal of that study and the wool traits were analyzed over a longer time period which helps to explain how they were able to make a much more dramatic change in the fiber diameters than was observed in this study. The stud flock of Uruguayan Merinos analyzed by Ciappesoni averaged 17 μm for fiber diameter (Ciappesoni *et al*., 2013). Another study that followed Australian Merino sheep over the lifetime of a sheep found that fiber diameter increased up to 6 years of age (Safari *et al*., 2007) which also contributes to a greater average fiber diameter of the Merino sheep because Mortimer analyzed ewes throughout their lifetime rather than a few years as in the studies that included Rambouillet sheep conducted by Aimone *et al.* and Bromley.

Despite greater clean fleece weights and smaller fiber diameters in both breeds Aimone *et al.* reported shorter relaxed average staple lengths of the two groups than those found in this study at 7.1 cm for the Rambouillet ewes and 8.0 cm for the Merino Rambouillet F1 cross ewes (Aimone *et al*., 1999). Bromley also observed similar unadjusted average staple lengths to Aimone in Rambouillet sheep as they averaged 7.2 cm with a standard deviation of 2.9 cm (Bromley *et al.*, 2001). Hanford found staple length averages of only 7.7 cm throughout the duration of their study (Hanford *et al.*, 2004). Oliver discovered only 0.10 cm difference in staple lengths between the two lines in that study but on average the MR ewes and rams in the present study both averaged over 1 cm longer staple lengths than were reported by Oliver *et al.*, (2007). Average staple lengths for the Uruguayan Merino flock (Ciappesoni *et al.*, 2013) were shorter at 7.9 cm than the average staple lengths of both genotypes in the present study.

Fabric Results

The garment portion of this project began with the purchase of 227 kg of wool top corresponding to the average fiber diameter of the MR and the R fleeces based on the calculation of simple averages of all of the ewes born into the study. The OFDA 4000 results were taken from the wool top prior to spinning yarn. The results from the WCM are presented in Table 13.

Table 13: OFDA 4000 Results of the Wool Top

	Genotype	
Fiber Characteristics	MR[a]=18.8 µm	R[b]=19.9 µm
Average Fiber Diameter, µm	18.52	19.45
SD AFD, µm	3.50	3.90
CV AFD, %	19.00	20.10
Hauteur, mm	65.70	66.30
CV Hauteur, %	44.60	47.10

[a] MR= Merino x Rambouillet, [b] R= Rambouillet

Table 14: Wool ComfortMeter Results

Top	Knit Structure	
Micron	Single	Interlock
18.8	479.7	331.3
19.9	464.9	499.2

The 19.9 µm single jersey knit fabric sample had more preferable WCM reading than the 18.8 µm sample. However, when comparing these WCM readings to those from additional studies it shows that the difference in fiber diameter does not account for all of the potential prickle-related discomfort that is common amongst wool fabrics. For example, in a study conducted by McGregor in Australia analyzed fabric knit from varying diameter wool top that had two different samples each with an average fiber diameter of 19.1 µm. The first 19.1 µm sample McGregor tested had a WCM score of 391 with a wearer prickle score of 2.35, coefficient of variation of fiber diameter of 24.7% and the percentage of fibers greater than 27 µm was 3.62%. The other sample had a WCM score of 433 but it had a lower wearer prickle score of 1.89, a lower coefficient of variation of fiber diameter at 22% and a lower percentage of fibers greater than 27 µm at only 3.22%. The sample with the 391 WCM score did have a higher overall WHM reading and the two fabrics differed greatly in fabric mass, illustrating that additional factors, such as fiber length, yarn winding tension, and fabric mass per unit area can significantly affect WCM results and the consumer's perception of the comfort of fabrics (McGregor *et al*., 2015). The yarn in the current study and in McGregor's were both spun of single ply yarns at a similar yarn size.

When comparing the results of the current study to those in McGregor's study the fabrics tested similarly on the WCM. As was reported in this study there were a few instances of finer average fiber diameter fabric samples with higher scores than those observed, such as a 17.2 µm sample that had a WCM score of 459. Despite the WCM not yet being fully approved to compare the results of interlock fabrics with single knit fabrics the samples tested in this study did perform as expected based on average fiber diameter. Naebe *et al*., 2015b did test one interlock knit fabric with an average fiber diameter of 20.6 µm and reported a WCM score of 463. The yarn used in the interlock sample was spun the same as samples reported in McGregor's study.

The research being conducted in Australia with the Wool ComfortMeter suggests that average fiber diameter accounts for the majority of the variance in the prickle sensation from wool fabrics. However, the influence of variation in fiber length has now been explored further since the development of the WCM. Although the focus has typically been directed to the percentage of fibers greater than 30 µm inducing prickle, researchers have found that much finer fibers, even those finer than 10 µm, are capable of triggering the prickle response if the free length protruding above the fabric surface is sufficiently short (Naebe *et al.*, 2015b). Thus, it is likely that yarn construction methods which influence the incidence of prickle inducing fibers in the fabric are also likely to affect the susceptibility of fabrics to induce prickle discomfort giving further credibility to WCM, as the numerical values produced are in overall agreement with the values from human responses (Naebe *et al.*, 2015b). When analyzing yarn on the WCM, Naebe also found that when the yarn WCM values are available, the average fiber diameter provided little or no extra value in predicting fabric WCM values. They again detected significant effects from yarn count, yarn ply and fabric mass per unit area on fabric WCM values (Naebe *et al.*, 2015b).

Table 15: Wool HandleMeter Results

Mic-ron of top	Knit Structure	Overall	Hard/ Soft	Rough/ Smooth	Loose/ Tight	Light/ Heavy	Clean/ Hairy	Cool/ Warm	Greasy/ Dry
18.8	Single	5.1	5.8	4.5	5.3	2.7	5.9	6.3	7.3
	Interlock	1.8	2.5	1.2	6.8	6.8	7.2	8.9	9.5
19.9	Single	5.3	5.9	4.7	5.2	2.6	5.7	6.3	7.2
	Interlock	2.0	2.7	1.6	6.7	6.6	6.7	8.4	9.4

The results from the WHM show both the 18.8 µm fabrics with slightly better handle properties overall. Again the WHM was only developed to assess single jersey knit fabrics so the interlock knit fabrics in this study can only be compared to each other. The two single jersey samples had very similar readings across all of the WHM indexes. Although smoother, the 18.8 µm fabric sample was slightly hairier than the 19.9 µm sample, which could help explain why it performed better on the WCM. When comparing these results to those found by McGregor, the scores for all indexes are very similar except for the light/heavy index (McGregor *et al*., 2015). The single jersey fabrics developed in this study were much lighter in weight than those tested in McGregor's study. The Australian fabrics did tend to be slightly smoother, greasier, and cooler based on the WHM indexes.

In direct contrast to the WCM, the WHM is a poor predictor of fabric evoked prickle discomfort. However, the WHM is a valuable tool when analyzing the handle characteristics of lightweight wool single jersey knit fabrics to aid in determining the type of garment the fabric should be used in.

Figure 4: Ideal Indexes for Active Wear and Every Day Wear

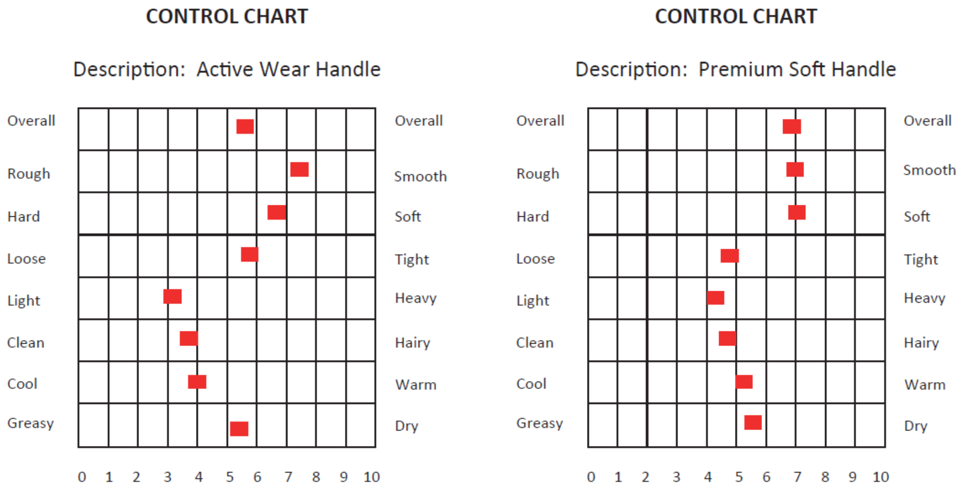


Figure 4 shows control charts that were developed to show the ideal indexes for all seven attributes for both active wear and every day wear fabrics. The chart on the left shows the ideal indexes for a crisper, cooler hand feel suitable for active wear and the chart on the right shows the ideal indexes for a warmer, softer garment, more suitable for luxury fashion products.

Abrasion resistance was tested via test method ASTM D 4966 using a Nu-Martindale Abrasion tester and a standard wool abradant fabric. The end point for this study was defined as the number of rubs to produce a hole in the fabric. Table 16 shows the results of the abrasion resistance testing. The results show that both of the 18.8 µm fabrics had a higher number of rubs before a hole was formed in the fabric. The 19.9 µm jersey fabric had the greatest variation amongst the three samples tested whereas the 19.9 µm interlock fabric had the least variation between samples tested.

Table 16: Abrasion Resistance Test Results

Micron of top	Knit Structure	Average # of rubs to endpoint	Standard Deviation of Average # of rubs to endpoint
18.8	Single	10,933	404
	Interlock	18,433	404
19.9	Single	9,400	964
	Interlock	17,967	153

Pilling resistance and other related surface changes of the fabrics was tested via test method ASTM D 4970 using a Martindale Tester. Samples were rated by comparison to photographic standards on a scale from 1-5 where 1 = very severe pilling and 5 = no pilling. Ratings were conducted every 100 movements up to 1000 movements. Four samples of each fabric and micron type were tested. A VeriVide (VeriVide Limited, Leicester, UK) apparatus for standardized assessment was also used to visually rate the samples. The pilling resistance test results are shown in Table 17. All four fabrics showed severe pilling after 1000 movements. The 19.9 µm single jersey fabric only showed moderate pilling after the first 100 movements on all test samples but showed very severe pilling after the next 100 movements. All other fabrics showed very severe pilling following the first 100 movements.

Table 17: Pilling Resistance Test Results

		Pilling Rating After 100 Movements by Sample			
Micron	Knit Structure	1	2	3	4
18.8	Single	1.0	1.0	1.0	1.0
	Interlock	1.0	1.0	1.0	1.0
19.9	Single	2.5	3.0	2.5	3.0
	Interlock	1.0	1.0	1.0	1.5

Fabric strength was tested via ASTM D 3786, bursting strength of textile fabrics – diaphragm bursting strength tester method. The results of this test are in Table 18. In both the single and interlock knit fabrics the 18.8 µm fabrics were considerably stronger than the 19.9 µm fabrics. However, the 19.9 µm interlock knit fabric showed the least variation throughout the ten test samples.

Table 18: Diaphragm Bursting Strength Test Results

Micron	Knit Structure	Adjusted Mean	Standard Deviation	Coefficient of Variation %
18.8	Single	32.48	3.18	9.80
	Interlock	53.33	2.92	5.48
19.9	Single	29.98	2.97	9.98
	Interlock	52.62	1.75	3.33

The dimensional change of fabrics after home laundering was tested via AATCC test method 135. All of the fabrics were washed in the normal/cotton sturdy machine on the warm setting and line dried. All fabrics experienced small amounts of growth in the length, especially the single jersey fabrics. All fabrics also experienced a small percentage of shrinkage in the width of the fabric.

Table 19: Dimensional Change of All Fabrics

Mic	Knit Structure	% Dimensional Change Length	Width
18.8	Single	8.8	-8.2
	Interlock	2.6	-8.6
19.9	Single	9.6	-8.2
	Interlock	2.8	-6.8

Note: Negative sign indicates shrinkage, positive sign indicates growth

Three additional washing techniques were conducted on both the single and interlock 19.9 µm fabrics to analyze any changes based on different common laundering settings. The fabrics washed in cold water and line dried experienced very similar results to the dimensional changes to those washed on the warm setting and line dried. Surprisingly, the interlock knit fabric showed less shrinkage in the width when tumble dried than when line dried. But, the interlock knit did experience a small percentage of shrinkage in the length as well. However, the single jersey fabric experienced greater shrinkage in the width when tumble dried rather than line dried. Various finishing techniques are available to eliminate these types of dimensional changes from occurring at the fabric level. The dimensional stability of a fabric can also be taken into account prior to the manufacturing of garments that will be steamed or laundered before they reach the retailer to achieve the proper fit.

Table 20: Dimensional Stability of 19.9 µm Fabrics

	% Dimensional Change Cold Water/ Line Dried		Cold Water/ Tumble Dried		Warm Water/ Tumble Dried	
Knit Structure	Length	Width	Length	Width	Length	Width
Single	9.3	-10.4	2.0	-13.2	7.5	-13.5
Interlock	2.7	-12.3	-3.3	-8.2	-2.9	-4.0

Fabric colorfastness to crocking was tested via AATCC test method 8, the crockmeter method. The results were rated using the AATCC gray scale for staining (GSS) where 5 = no staining and 1 = significant staining. The colorfastness to crocking results are listed in Table

21. The dry fabric crocking test showed very little crocking and did not differ based on micron diameter or fabric thickness. The wet fabric crocking test showed more color transfer on to the test fabric. The 18.8 interlock fabric showed slightly less color transfer than the other three fabrics. This test method is truly a test of the dyeing and finishing processes used rather than measuring differences due to micron or knit structure. However, these tests are important to understand how the dye reacts with the wool.

Table 21: Colorfastness to Crocking: Crockmeter Method Test Results

		Crocking – Gray Scale for Staining	
Mic	Knit Structure	Dry (Face)	Wet (Face)
18.8	Single	4.5	1.5
	Interlock	4.5	2.0
19.9	Single	4.5	1.5
	Interlock	4.5	1.5

Colorfastness to perspiration was tested via AATCC test method 15. The test fabric fading was rated using AATCC gray scale for color change (GSCC) where 5 = no change and 1 = significant change. The staining of other fabrics was rated using the AATCC gray scale for staining (GSS) where 5 = no staining and 1 = significant staining. The multi-fiber fabric number 10 was used to assess color transfer on to wool, acrylic, polyester, nylon, cotton, and acetate. The test results are shown in Table 22. All four fabrics showed no fading and no staining of other fabrics due to perspiration.

Table 22: Colorfastness to Perspiration Test Results

		Gray Scale for Staining						
Mic	Knit Structure	Fading (GSCC)	Wool	Acrylic	Polyester	Nylon	Cotton	Acetate
18.8	Single	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	Interlock	5.0	5.0	5.0	5.0	5.0	5.0	5.0
19.9	Single	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	Interlock	5.0	5.0	5.0	5.0	5.0	5.0	5.0

Final Garment Results

The four garment configurations that were tested on the sweating thermal manikin system are listed in Table 23.

Table 23: Ensemble Identification

Ensemble Code	Test Sample
A	18.8 Micron Shorts and Short Sleeved Shirt
B	19.9 Micron Shorts and Short Sleeved Shirt
C	18.8 Micron Shorts and Long Sleeved ¼ Zip Shirt
D	19.9 Micron Shorts and Long Sleeved ¼ Zip Shirt

The manikin wore only the test garment (i.e. no undergarments, etc.). The test shirts were tucked into the test shorts to eliminate any movement or billowing effects from the shirt due to wind speed. Both the total thermal resistance and total evaporative resistance are provided by the manikin, garment ensemble and the air layers. The intrinsic thermal resistance and intrinsic evaporative resistance scores are only provided by the garment ensembles. The total insulation value, expressed in units of clo, is the total insulation provided by the manikin, garment ensemble, and air layers. Clo is a measure of thermal resistance and takes into account the insulation provided by any layer of trapped air between skin and clothing as well as the insulation value of clothing itself. Clo indicates the insulating ability of the test material. Materials having higher clo values provide wearers with more thermal insulation. A clo value of 1 represents a typical man’s business suit and is expected to maintain thermal comfort for a person in a normal indoor environment. Typical requirements vary from about 0.5 clo for summer wear to 4 to 5 clo for outdoor winter clothing. The permeability score indicates moisture-heat permeability through the material on a scale of 0 (totally impermeable) to 1 (totally permeable). Predicted heat loss gives a predicted level of the total amount of heat that could be transferred from the manikin to the ambient environment for a specified condition. It uses the thermal and evaporative resistance values to calculate predicted levels of evaporative and dry heat transfer components for a specific environmental condition. The full body sweating manikin test results are shown in Table 24 followed by the test results for the short sleeve zones only in Table 25 and the long sleeve zones in Table 2

Table 24: Full Body Sweating Manikin Results

Ensemble	Total Thermal Resistance	Total Evaporative Resistance	Intrinsic Thermal Resistance	Intrinsic Evaporative Resistance	Total Insulation Value	Permeability Index	Predicted Heat Loss Potential
A	0.0977	0.01518	0.0220	0.00355	0.63	0.39	337.3
B	0.0972	0.01569	0.0229	0.00393	0.63	0.38	330.2
C	0.1075	0.01676	0.0323	0.00478	0.69	0.39	305.8
D	0.1095	0.01679	0.0342	0.00499	0.71	0.40	303.7

Table 25: Short Sleeve Zones Only Sweating Manikin Results

Ensemble	Total Thermal Resistance	Total Evaporative Resistance	Intrinsic Thermal Resistance	Intrinsic Evaporative Resistance	Total Insulation Value	Permeability Index	Predicted Heat Loss Potential
A	0.1817	0.02778	0.0942	0.01348	1.17	0.40	183.5
B	0.1815	0.02800	0.0956	0.01354	1.17	0.40	182.5

Table 26: Long Sleeve Zones Only Sweating Manikin Results

Ensemble	Total Thermal Resistance	Total Evaporative Resistance	Intrinsic Thermal Resistance	Intrinsic Evaporative Resistance	Total Insulation Value	Permeability Index	Predicted Heat Loss Potential
C	0.1996	0.02683	0.1155	0.01328	1.29	0.45	183.2
D	0.1815	0.02865	0.1244	0.01529	1.35	0.44	172.5

Thermal resistance is a measure of a garment’s ability to prevent heat from flowing through it. Both fabrics at both microns had adequate levels of total and intrinsic thermal resistance and in the zone-specific tests the 18.8 µm fabrics showed slightly higher levels of thermal resistance. Both the 19.9 µm fabrics had greater total and intrinsic evaporative resistance scores in both the full body and zone specific tests. The evaporative heat loss is the best single physiological index of the environmental stress. The insulation values identical at in both the full body and zone-specific tests for the short-sleeve shirt and shorts. The insulation values show these garments work well not only in warm summer temperatures but also in cooler temperatures as well. Surprisingly, the permeability measured between both the single jersey and the interlock knit did not differ as greatly as would typically be expected between fabrics of different weights. The permeability scores did not differ greatly between the two microns either. The predicted heat loss potential was higher for the 18.8 µm fabrics across both the full body and zone-specific tests. Higher heat loss potential scores indicate a greater heat transfer capability of the fabric which is necessary to keep the body comfortable especially when being active. Wicking or hydrophobic clothing has a negative effect on body’s evaporative cooling (Wang *et al*., 2014). Wang also found in a previous study that the real evaporative cooling efficiency increases with increasing thermal insulation (Wang *et al*., 2011). Based on the sweating manikin results both microns performed very similarly however the 18.8 µm garments consistently showed higher predicted heat loss potential which is optimal to keep the body comfortable in warmer temperatures.

CONCLUSION

The results of this study are similar to findings of the studies reviewed for the live-animal portion of this project. However, some of the differences between the two breeds are not as apparent as they were in previous studies. The advancements made within the Rambouillet breed in the United States and especially in Texas can partially be attributed to over 60 years of a central performance ram test conducted by Texas A&M University. This study included sires from that test. Overall, between the two breeds weaning weights were similar especially between the rams born into the study. Selecting for individual lamb weaning weight can improve lamb growth, selecting solely for that trait could decrease total lamb production per ewe (Snowder *et al*., 1997b).

Although all wool must undergo a scouring process before yarn is produced, the processing industry much prefers higher yielding, cleaner fleeces due to the increased efficiency realized when scouring those fleeces. The heavier fleeces produced by the MR can be associated with the longer staple fibers of those fleeces but both groups produced acceptable staple lengths for the processing industry. However, wool produced in the U.S. consistently sells for about 80% of the price of Australian wool. Different climates contribute greatly to the differences in yields and subsequent processing between these two populations. An unforeseen shift in wool prices occurred throughout the period of this study. A much greater price differential was present at the start of this study between 18 and 20 µm wools as shown in Table 27. Unfortunately for producers of wool finer than 20 µm, today due to increased production of superfine (≤18.5µm) and fine wool (18.5-20µm) worldwide (but particularly in Australia) and a lack of volume in the mid-range of strong (21-26µm) wool, prices have tended to be less variable among the various micron counts (Table 28).

Table 27: U.S. fine-wool prices as of March 1, 2006

Average Fiber Diameter, µm	Price, $/kg, clean	Gross value of wool/ewe/year, $
18.5	11.62	29.05
20.0	5.40	13.50
21.0	4.94	12.35
22.5	4.85	12.13

Table 28: U.S. fine-wool prices as of September 17, 2015

Average Fiber Diameter, µm	Price, $/kg, clean	Gross value of wool/ewe/year, $
18.0	10.21	25.52
19.0	9.83	24.58
20.0	9.28	23.20
21.0	9.15	22.87
22.0	9.11	22.76

Tables 27 and 28 illustrate the changes in wool prices by average fiber diameter from the start of the study and from the current year. Table 27 shows wool prices for March, 2006 based on average fiber diameter and assumes a ewe would grow 2.5 kg of clean wool per year. Table 28 also shows wool prices from September, 2015 based on average fiber diameter and also assuming a ewe would produce 2.5 kg of clean wool per year. These tables illustrate the changes in sale price over the past ten years for the types of wool grown globally. Many producers have tried to decrease the average fiber diameter of their wool clip or have gotten out of the wool business completely, which has led to a decrease in supply of 20 µm and coarser wools and the levelling of prices based on fiber diameter.

In general, the 18.8 µm fabrics and garments performed better or very similar to the 19.9 µm fabrics and garments across all of the tests performed. However, both the 18.8 µm and 19.9 µm fabrics and garments performed adequately for use in the active-wear market. As the active wear and casual wear markets continue to grow, these results show there is much room for growth of wool products within this market segment. Especially considering the advancements made in the ease of care of garments made from wool.

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