Journal of Textile and Apparel, Technology and Management

Volume 7, Issue 1, Spring2011

Thermal Pattern Variations Analyzed Using 2D/3D Mapping Techniques among Females

Tanya Domina, Professor
Apparel Merchandising & Design
Central Michigan University

Patrick Kinnicutt, Associate Professor
Computer Science
Central Michigan University

Maureen MacGillivray, Professor
Apparel Merchandising & Design
Central Michigan University

ABSTRACT

Background: Today it is technologically possible for textile/apparel companies to map different fiber, yarn, fabric, finish and design variations to specific body areas, facilitating heat and moisture management. 2D/3D thermal mapping places a flat 2D thermal image onto a 3D body scan, creating a thermal map or thermal profile of the individual. 2D/3D mapping offers the apparel industry the opportunity to design garments that are customized by function as well as by fit – a key to global competitiveness in the 21st century. Furthermore, thermal profiling has consumer implications as well, and may provide new opportunities for consumers to participate in the design process, creating a garment suited to the individual's thermal profile or map.

Purpose: The objective of this study is to explore the development of a process by which 2D thermal images can be mapped onto 3D body scans and then thermal variability compared.
Methodology: The subjects were mined from a database based on selection criteria of female, age 20-59 years, with a BMI that was either normal or obese. The subjects' thermal images were then mapped onto their 3D body scan and their thermal variability compared.

Findings: The findings suggest that a woman's thermal pattern or profile is a function of BMI and is not age dependent. Women with a normal BMI have different thermal distributions than women classified as obese.

Keywords: thermal patterning, 2D/3D mapping, thermal imaging, body scanning

Introduction

Opportunities abound for implementing technology into every aspect of our lives including the clothes we wear. Watkins (1995) conceptualized functional apparel as a "portable environment" whereby the body and the clothing perform together enhancing the body and its functions without compromising comfort or mobility. Functional apparel is demanded by 21st century consumers whose apparel needs are greater than for modesty or fashion alone. Depending upon its end use, functional apparel can be designed using a constellation of fibers, yarns, fabric structures and finishes. And with the use of 3d body scanning technology, apparel can be made to fit the precise measures of an individual. However, most clothing today is designed without consideration of individual differences in body dimensions or heat regulating capacity. Innovations in fibers, knitting and weaving technologies, and heat and moisture regulating finishes make possible the development of customized apparel of heterogeneous materials that can intelligently manage heat retention or loss. The capability of defining body locations with low and high heat production will allow textile/apparel companies to map different fiber, yarn, fabric, finish and design variations to specific body areas, facilitating the engineering of highly innovative, customized garments for a wide variety of markets and end-uses. The 2D/3D body mapping process offers the apparel industry the opportunity to design garments that are customized by function as well as by fit – a key to global competitiveness in the 21st century.

2D/3D mapping can be defined as the process of placing (mapping) a flat 2D bitmap image onto a flat or curved 3D image. In this on-going research project, 2D thermal images of the torso region have been mapped onto a 3D body image then thermal variability compared. Although the mapping process is used by a variety of industries, it is particularly well suited to apparel design and development; including next-to-skin garments, athletic apparel, biomedical devices or accessories, protective clothing, "smart" clothing, hot and cold weather clothing systems for the military, and protective wear for first responders; virtually any type of apparel worn outside the thermal-neutral zone. Knowledge of consumers' thermal patterns will provide the information designers and product developers need to create garments with targeted heat retention or heat releasing zones of specific sizes and locations designed to help keep the wearer in thermal balance. Additionally, these individual thermal maps can be collected, resulting in a thermal profile for a group of consumers based on specific body characteristics.

Background and Justification
Thermoregulation

Thermal balance is achieved when the amount of heat produced by the body is equal to the amount of heat dissipated by the body. Humans are able to maintain a stable body core temperature in spite of widely varying environmental conditions and metabolic activities through thermoregulation. Whether one is running or walking in the cold or in the heat, the body maintains a constant core temperature through thermal regulating mechanisms that endeavor to maintain thermal balance. Most clothing produced today does not consider variations in how and where the skin dissipates heat and perspiration. The location and amount of perspiration varies by body area and is affected by exercise intensity (Kulka & Kenney, 2005; Ueda, Inoue, Matsudaira, Araki, & Havenith, 2006; Wong, Li, & Yeung, 2002; Yoo & Barker, 2005). If one or more of the thermal balance factors are varied, i.e., environmental temperature increases or decreases, or metabolic activity increases or decreases, regulating mechanisms will be triggered to bring the body back into heat balance (Kinnicutt, Domina, MacGillivray, & Lerch, 2008).

Morphological and somatotype variations (size, body composition, skin surface area), physiological variations (gender, age level of fitness, heat acclimation), environmental conditions (temperature and humidity), and type of clothing, all influence the individual differences in thermal regulation (Ashley, Luecke, Schwartz, Islam, & Bernard, 2008; Pascoe, Shanley, & Smith, 1994; Passlick-Deetjen & Bedenbender-Stol, 2005). Early research linking morphology to thermoregulation focused on an individual's amount and location of fatty tissue and skin surface area and then later, the role of muscle in thermoregulation in a variety of environments (Anderson, 1999). However, after 50 years of research, there is still little consensus as to the relationship between morphology and thermoregulation. As stated by Anderson (1999), "Individuals differing in body size, shape and composition appear to respond quantitatively differently to variations in both ambient and core temperatures, but the interrelations between morphological components and temperature regulation are complex" (p. 99). A study of military men and women found that individuals, classified into five major somatotype groups, responded to heat stress differently based on their somatotype (Yokota & Bathalon, 2008). Savastano et al., (2009) found that obese adults displayed different thermal patterns on the belly region than their thinner counterparts. In sum, although the link between somatotype and thermal regulation is still cloudy, there does appear to be some relationship.

Age also has an impact on an individual's ability to thermoregulate. Most research indicates that an individual's thermoregulatory response decreases with age; with the elderly particularly disadvantaged by the cold (Herbert & Rowswell, 2006; Inoue, Nakao, & Ueda, 1992; Khan, Spence, & Belch, 1992; Pascoe et al.,1994; Taffett, 2003; Wagner, Robinson, & Marino, 1974). However, in a recent study by Lu & Dai (2009) results indicated that older does not automatically mean colder and that ambient temperature and gender play a larger role in thermal regulation than age alone.

Clothing systems are a critical factor in an individual's ability to maintain thermoregulation because the clothing system's thermal properties interface with the body and the ambient environmental conditions (Branson and Sweeney, 1991; Holm, 2006). There is extensive research on heat and moisture transfer in clothing and its ability to assist with thermoregulation (Ashley et al., 2008; Celcar, Meinander, & Gersak, 2008; Fan & Cheng, 2005; Farnworth, 1986; Gavin, 2003; Kinnicutt et al., 2008; Li & Holcombe, 1998; McCullough, Jones, & Huck, 1985; Olesen, 1985; Voelker et al., 2009; Wissler, 2009; Woodcock, 1962; Wu & Fan, 2008). This demonstrates the potential usefulness of a 2D/3D mapping process that guides the development of garments designed to specifically handle thermal regulation at the skin surface, taking into account individualized thermal patterns.

Body Scanning

Body scanners are a relatively recent technology whose main function is to measure the surface topography of the human body, producing a 3D image of the individual being scanned as well as an extensive list of body measurements. Recently, body scanners have been used in many areas of study and the resulting data make it uniquely suitable for academic and industry apparel research. Topics of recent study include: consumer perceptions of body scanning (Loker, Cowie, Ashdown, & VanDyk, 2004; McKinnon & Istook, 1999), limitations and the need for standardization (Istook & Hwang, 2001; Lerch, Anthony & Domina, 2008; McKinnon & Istook, 2002; Simmons & Istook, 2003), mass customization of apparel (Lee & Chen, 2000; Xu, Huang, Yu, & Chan, 2002) and analysis of body shape and posture for fit and garment reengineering (Ashdown & Na, 2008; Istook, 2000; Loker, Ashdown, & Schoenfelder, 2005; Petrova & Ashdown, 2008). The results of body scanning research help to promote the textile/apparel industries' mass customization efforts, offering the opportunity for garments to be customized ~~not only~~ to the general population as well as to the individual consumer.

When integrated with a sophisticated CAD system, the body scanner can provide the apparel designer with inspiration and more flexibility in conceptualizing prototypes and in altering and adapting existing products and processes, thus reducing design reiterations and expanding the possibilities for innovative solutions. The body scanner has the ability to assist the apparel designer in creating virtual garments by incorporating digital modeling for patterns. In studies of geometric pattern modeling, researchers found that virtual garments could be designed prior to the actual prototyping, reducing the waste of time and cost (Kang & Kim, 2000; Kim & Park, 2007). Ultimately, 3D body scanning will allow apparel designers to improve the product development process while better meeting the needs of their customers.

Thermal Imaging

A thermal camera makes use of an infrared imaging and measurement system to visualize and measure the thermal energy emitted from objects in the environment (Ferreira et al., 2008). Infrared (IR) energy is not visible to the naked eye because its wavelength is outside of the visible electromagnetic spectrum. In the infrared part of the spectrum, everything with a temperature above absolute zero emits heat, such as skin, and the greater the amount of IR energy emitted the higher an object's temperature. Thermal cameras using infrared technology are capable of discriminating temperature differences as small as 0.12°C, and may be used to assess the absolute temperature of specific points on the body, or alternatively to calculate average temperature of a specific region of the body as specified by the researcher. As is typical, thermal profiles generated by a thermal camera use different colors or grayscale gradations to visually quantify heat released by the body. The different colored boundaries allow for comparisons of the relative differences in the amount of heat released by one area of the torso as compared to other areas.

Since the 1980s, thermography has been used by a variety of different disciplines to study the thermal patterns of the body surface. This technology has been used by the medical community to help diagnose disease states as well as provide a means of quantifying rheumatoid arthritis, nerve injury, body composition, and obesity (Contaldo, Rocco, & Mancini, 1980; Frim, Livingstone, Reed, Nolan, & Limmer, 1990; Niu et al., 2001; Salisbury, Parr, De Silva, Hazleman, & Page-Thomas, 1983; Spalding, et al., 2008). Thermal patterning has been used by chiropractors to access autonomic function and paraspinal thermal patterns (Hart, Omolo, & Boone, 2007; Owens, Hart, Donofrio, Haralambous, & Mierzejewski, 2004; Roy, Boucher, & Comtois, 2006).

For the apparel designer, thermal infrared imaging systems can be used to visualize and measure skin and surface temperatures, providing an effective and innovative tool for designing apparel that takes skin temperature variation into consideration. Using thermal data as part of the design process also allows for greater efficiency and potential cost savings. For instance, expensive finishes such as phase change materials could be applied in regions where they would be most effective, as opposed to an overall application.

2D/3D mapping

2D/3D mapping can be defined as the process of placing a flat 2D bitmap image onto a flat or curved 3D image. Work on mapping 2D images to 3D objects has been used in various applications, such as with the visualization of Martian rocks (Basdogan , 2007) and face pose determination to track head and gaze orientation, often an indicator of inattention or fatigue (Ji & Hu, 2002). Additionally, 2D/3D mapping techniques are utilized by animation and graphic professionals to give a sense of realism to movies (Durand, 2002), for image-guided neurosurgery for the purpose of surgery guidance (Dey, Slomka, Gobbi, & Peters, 2000), and by meteorologists to create 3D land and satellite imagery (Croitoru, 2004).

2D/3D techniques have begun to be utilized by the apparel industry as virtual clothing design becomes more feasible in light of recent developments in software and computer technology. 2D/3D virtual apparel systems typically include three components: human body modeling, 3D pattern and garment modeling, and the simulation of fit and fabric texture and drape. Research efforts have focused primarily in two areas, fabric simulation and drape, and 3D pattern generation and fit analysis. Terzopoulos, Platt, Barr, and Fleischer (1987) pioneered fabric drape simulation using a variety of methods still employed today. Later researchers made contributions by improving drape, folds and realistic texture and movement to fabric simulation (Baraff & Witkin, 1998; Desbrun, Schroder, & Barr, 1998; Kang & Cho, 2002; Volino & Magnenat-Thalmann, 2005; Volino, et al., 2007). Simultaneously, research was underway to create 3D patterns and then visualize the virtual garment on an avatar for fit purposes. Zhong & Xu (2009) provide a detailed explanation of the processes necessary for virtual garment generation and fit. Kim & Park (2007) developed a pattern generation system which generates flat garment patterns by modeling and flattening the 3D garment models.

In the last twenty years, academicians and design software companies have combined these avenues of research to create fully integrated 2D/3D CAD systems for both apparel designers and product developers. P-smart is a virtual CAD system that was developed to allow designers to include thermal functional performance as part of the design process (Yi, et al., 2006). Lectra System Technologies recently released Modaris 3D Fit™ software allowing designers and product development teams to visualize garment styles and associated patterns in a 3D environment on an avatar. This allows for the look and fit of the garment to be verified prior to sample production (Reuters, 2008). Other providers of 2D/3D design simulation software include Optitex™, Browzwear™, and Bernina USA™ among others. It is expected that apparel firms will increasingly explore 2D/3D design solutions in order to reduce cost, increase efficiency and better serve the needs of their customers.

Today’s consumers express the desire for apparel that is customized to their bodies as well as to their wants and needs, such as for cycling or running in the rain. The capability of 3D body scanners and associated software makes it feasible to design customized apparel for the individual by mapping 2D thermal information recorded by the infrared thermal camera to the body topography generated by a 3D scan. The result is a “body map” that can be used to guide the development of a garment that allows for appropriate heat and moisture exchange between the body and the environment.

Purpose

The purpose of this long-term research project is to explore the development of a process by which 2D thermal images can be mapped onto 3D body scans and then thermal variability compared.

Method

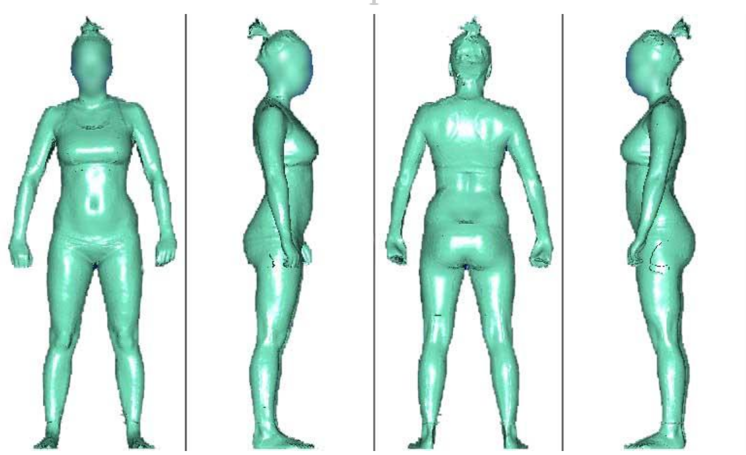
This ongoing research project includes the use of a 3D body scanner and a FLIR thermal camera with subject recruitment and data collection. The database currently contains over 850 individuals, comprising both male and female subjects, from 16 to 92 years old. The subject population consists of persons with sedentary to active lifestyles, diverse heights, weights, body mass index (BMI) ratios and somatotypes. After receiving Human Subject Review approval, subjects were recruited using a variety of methods as appropriate for the age category. Subjects under 18 were recruited primarily through the local public school system, summer camps and other pre-university activities and events designed to attract potential students. College students, faculty and staff were recruited through on-campus email and online university announcement systems. Adults outside the university community were recruited through presentations at professional and service organizations, newspaper and radio, flyers throughout the local community, and word of mouth. The older adult subjects were recruited from local nursing homes, assisted living communities and in collaboration with the Commission on Aging. Subject recruitment is an on-going activity with new subjects being added to the database on a weekly basis.

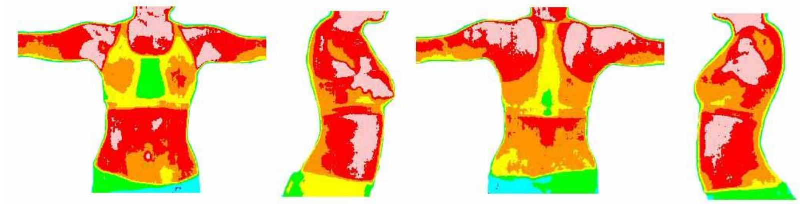
The steps used in the 2D/3D mapping process for integrating the thermal images and the 3D body scan onto a single model are: (1) data collection; (2) thermal image clean-up; and (3) image registration and mapping. The remainder of this section describes each step in more detail.

Data Collection

The initial phase of this process involves data collection. During this phase, each subject is scanned utilizing a Human Solutions VITUS/smart 3D body scanner. The body scanner is self-calibrating, has 8 cameras and four laser light sources, and collects approximately 300,000 digital data points from each scanned subject within 12 seconds. For accuracy, each subject is minimally clothed in form fitting garments such as undergarments, aerobic shorts and sports bra, or swimsuit. After scanning, the subject next stands in front of a self-calibrating thermal camera with a black backdrop, where thermal images of the subject's front, left, right and back torso areas are taken at ambient conditions. Subjects are then weighed and asked to fill out a standard demographic and exercise frequency questionnaire. Lastly, the subjects' information is entered into a non-personalizable database. Figure 1 displays four views of a subject's 3D body scan (on the top) and their thermal images (on the bottom). As presented in Figure 1, the subject poses five separate times (1 3D scan and 4 thermal images); problems associated with resolving the various stances as well as with mapping the 2D images onto a 3D coordinate space must be addressed. Cleaning the thermal images must also be addressed; preprocessing these images involves erasing "noise" from the surrounding background and removing the arms and head, which are not needed for the 2D/3D mapping of the human torso. These issues are addressed through the processing steps described below.

Figure 1. Four views of the 3D body scan (top images) and four thermal images (bottom images) for the front, left, back and right sides of the same subject

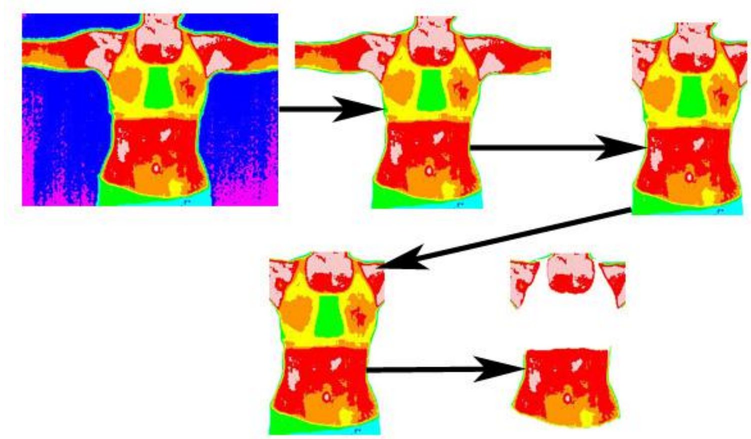




Thermal Image Cleanup

Once the data has been collected, processing of the thermal images is then performed. A primary objective for this project involves creating a thermal database of the human torso for data mining, to support the design of innovative mass-customizable functional apparel which optimizes individual thermal comfort under various activity levels. The authors have limited the scope of this project to only the human torso, but this process can be extended to other parts of the body. As seen in Figure 2, the thermal images contain "noise" in the form of background temperatures and non-torso temperature regions. This thermal image cleanup step is a required pre-processing step to 2D/3D mapping, to ensure that only the torso temperatures are mapped onto the body scan and to simplify that process. Initially, these thermal images were cleaned manually using Adobe Photoshop and visual inspection. However, as the number of subjects—increased an automated image object recognition technique was developed to increase productivity and reduce the time for completing the 2D/3D mapping.

Figure 2. Process used to remove the background noise from the thermal images



The image object recognition technique was used to determine the thermal boundaries of the human in order to remove the background noise from the thermal image as well as to remove arms, head and the area covered by the undergarments since this data is not needed for this project. Figure 2 provides a visual representation of the steps used in cleaning the image.

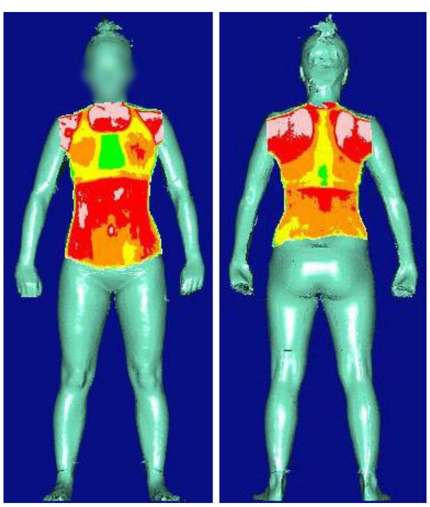
Image registration

Once the thermal images have been cleaned, the next step involves mapping the temperatures onto the 3D object. This general process is known in computer science as UV mapping (Franken et al., 2005), and involves the use of image registration techniques as described by various authors over the past two decades (Brown, 1992; Fengzhi and Li, 2005; Goshtasby, 2005). Image registration is required to map the 2D thermal images onto the 3D body scan of a specific subject because during the data collection procedure, the subject poses five separate times. Each time the subject poses they stand or lean in different orientations, and they also position their feet slightly differently; image registration is a general process by which these differences are resolved (Brown, 1992).

Essentially, image registration makes use of common landmarks which exist on both the thermal images and the 3D scan. These landmarks may be either anatomical landmarks visible in both images or interfaces; examples of anatomical landmarks may be the umbilicus, clavicle, and spinal cord, while interface examples may be the interface between the sides of the torso or the interface between the torso and undergarments. From the common landmarks, correlation analyses are used to determine the coordinate and projection transformations required so that the landmark locations all coincide. For a detailed discussion of image registration techniques see Fengzhi & Li, 2005; Franken et al., 2005; or Han & Bhanu, 2005.

The result of image registration is presented in Figure 3.

Figure 3. Front and back thermals after 2D/3D mapping process

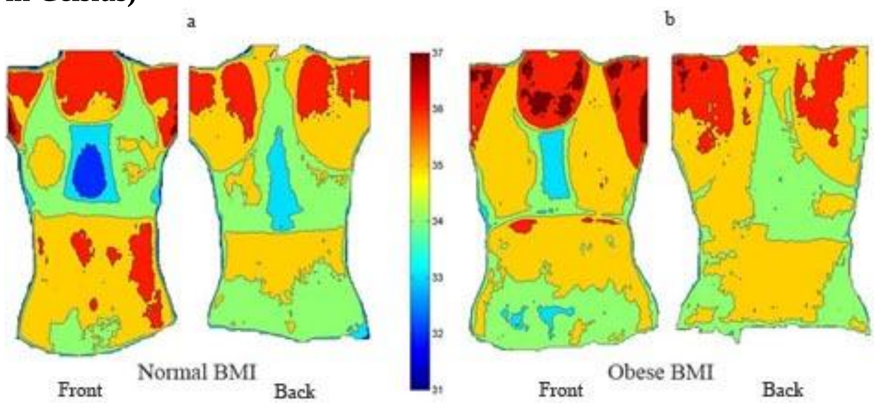


The 3D body scan with its accompanying 2D thermal image mapped on to it can still be manipulated, posed or rotated in 3D. From these mapped images, apparel firms can produce clothing with more effective thermal functional performance. This includes the structural features of clothing assemblies, as well as special finishes or knit in structures designed to manage heat and moisture.

Thermal patterns

Before comparisons can be made the amount of thermal data for each individual must first be reduced. On average, the thermal camera creates a thermal representation of the human torso with an average of 50 thousand valid pixels (on the human torso) per subject, each representing a temperature value. One technique used to examine the spatial variability of temperatures consists of contouring the temperatures, as one would do in a topographical map. The purpose of this contouring is to determine the regions of equal temperature, and to also determine the temperature gradients as a function of location. Each contour line represents an isoline, or line of equal temperature. An isoline is generally (but not always) an enclosed loop where everything immediately inside the loop has a greater temperature than the isoline temperature and everything immediately outside the loop is a lower temperature (Figure 4). One feature of using contour lines is that areas can be calculated within the lines representing the spatial region exceeding the temperature represented by the isoline. The contours were created using contouring algorithm from the *contourc* Matlab function, with 5 contouring levels. After the contour levels have been created, a thermal rating for each individual is calculated. The thermal rating is a function of the spatial variation in the human torso, based on the number of contour lines present and the areas of the contour regions. A low rating, or fewer contours, corresponds to a uniformly distributed thermal profile, while a high rating, more contours, corresponds to a high spatial variation of temperature.

Figure 4. Contoured thermal images of (a) normal BMI and (b) obese BMI (temperatures in Celsius)



In order to compare thermal variability, a sub-sample of subjects was used. The subjects were mined from the database based on selection criteria of gender (female), age 20-59 years, and a BMI (Body Mass Index) that fell into either the normal range of 18.5-25 or obese greater than 30. Table 1 presents the summary data by age category and BMI (normal and obese).

Table 1. Subjects by age range and body mass index (BMI)

Age range	BMI classification	Frequency	Mean BMI	S.D.	Min.	Max
20-29	Normal 18.5-25	29	21.46	1.97	18.55	24.36
30-39	Normal	29	22.45	1.51	19.37	24.98
40-49	Normal	34	22.21	1.64	18.69	24.81
50-59	Normal	25	22.09	1.66	18.95	24.53
20-29	Obese > 30	11	36.34	4.08	30.92	44.28
30-39	Obese	12	38.64	5.21	30.64	44.85
40-49	Obese	11	33.67	3.19	30.71	42.17
50-59	Obese	8	34.36	3.98	30.09	41.16

Results

Tables 2-1 and 2-2 present the results of the thermal variability comparison by BMI and age category. The average thermal rating is an indication of how uniform the thermal profile is; the larger the thermal rating, the more variability exists. Average thermal ratings for the four age categories were calculated by summing all the thermal patterns located on the torso for each individual, then dividing by the number of individuals in an age category. Thermal variability ranged from a low of 41.20 (40-49 years of age) to 43.13 (20-29 years of age); however, there was no statistical difference in the thermal ratings variability for age categories. Subjects were then grouped according to their BMI, normal or obese, and the thermal variability compared with results indicating that the two groups were statistically different ($p < .001$). Results indicated that individuals with a normal BMI exhibited less thermal variability (40.62) than did the obese individuals (47.69). This finding is consistent with previous research (Savastano, et al., 2009).

Table 2-1. ANOVA summary statistics by BMI category and age group

Summary Statistics	Frequency	Average thermal rating for torso	Variance	Minimum	Maximum
Groups					
BMI					
Normal	117	40.62	95.79	13	73
Obese	42	47.69	101.24	26	64
Age					
20-29	40	43.13	119.45	24	64
30-39	41	42.95	102.05	20	63
40-49	45	41.20	98.57	13	73
50-59	33	42.88	113.36	22	62

Table 2-2. ANOVA analysis by BMI category and age group

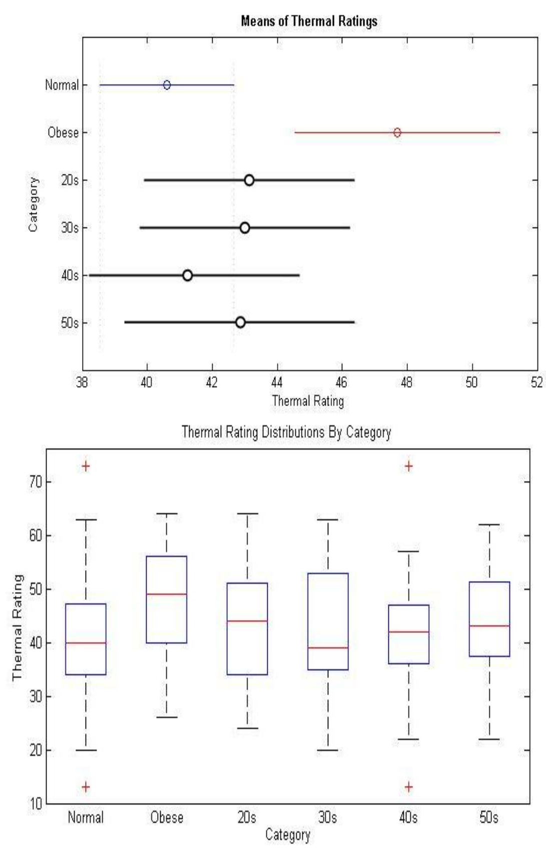
Grouping	Sum of Squares Between	Sum of Squares Within	F	Significance
BMI	1547.04	15262.67	15.91	0.0001
Age	104.72	16704.99	0.323	0.8081

Figure 5 displays a boxplot of the thermal ratings categorized first by BMI (Normal vs. Obese) then by age group along with a plot showing the means for each category, using a 95% confidence interval to bracket the means. Supportive of Table 2-2, Figure 5 shows that the means for the normal and obese BMI categories are significantly different, while the means as categorized by age are not significantly different. Also, Figure 5 shows that while there is some overlap in the thermal ratings between the normal and obese categories of females, over 75% of the normal subjects have a thermal rating less than the median for the obese female and over 75% of the obese subjects have thermal ratings greater than the median for the normal subjects.

As presented earlier in Figure 4, the obese subject located on the right displays lower temperatures in the lower abdomen compared to the subject with a normal BMI. The upper front torso region for the obese subject also typically emits more heat than for a normal subject from our data.

It can be concluded that BMI bands play a significant role in the thermal profiles

Figure 5. Top: Boxplot of thermal ratings by category; Bottom: Means of thermal ratings with 95% confidence Intervals



of individuals, whereas age has a lesser impact on thermal distributions.

Conclusions

The results of this study indicate that a woman's thermal pattern or profile when at rest is a function of BMI and is not age dependent. Women with a normal BMI have fewer thermal patterns and a more even thermal distribution, than do women classified as obese. It is likely that this difference is a result of the amount and distribution of subcutaneous fat in the torso region. Regardless of the reason for the variability, the results of this study have implications for industry professionals who design and market textiles and apparel that is meant to help regulate the thermal comfort of the wearer. The 2D/3D body mapping process and thermal profiling proposed here could be used by designers to guide the development of textiles and garments that best match the thermal profiles of their customers, providing superior functional and comfort performance. Thermal profiling has consumer implications as well, and may provide new opportunities for consumers to participate in the design process, co-designing a garment suited to the individual's thermal profile or map. Furthermore, knowledge of one's thermal profile provides important information when shopping for apparel for specific needs such as for different exercises, athletic events, work and other physical activities that take the wearer outside the thermal-neutral zone.

The results of this study indicate that there is value in continuing to explore thermal profiling and its benefits to designers and other industry professionals. Additional research needs to be conducted to determine if and how other variables such as ethnicity, level of physical fitness, or diet influence an individual's thermal pattern. Additionally, more research needs to be done on males, children and older adults. Continued research will hopefully lead to a set of common thermal patterns that can be used for mass marketing functional apparel with optimal performance and minimal cost to manufacture.

References

Anderson, G. S. (1999). Human morphology and temperature regulation. *International Journal of Biometeorology, 43*(3), 99-109.

Ashdown, S. P., & Na, H. (2008). Comparison of 3-D body scan data to quantify upper-body postural variation in older and younger women. *Clothing and Textile Research Journal, 26*(4), 292-307.

Ashley, C. D., Luecke, C. L., Schwartz, S. S., Islam, M. Z., & Bernard, T. E. (2008). Heat strain at the critical WBGT and the effects of gender, clothing and metabolic rate. *International Journal of Industrial Ergonomics, 38*(7-8), 640-644.

Baraff, D., & Witkin, A. (1998). Large steps in cloth simulation. In *Proceedings of ACM SIGGRAPH 98* (pp. 43-54), Washington, DC: ACM Press.

Basdogan, C. (2007). From 2D images to 3D tangible models: Autostereoscopic and haptic visualization of Martian rocks in virtual environments. *Presence, 16*(1), 1-15.

Branson, D. H. & Sweeney, M. M. (1991). Clothing comfort conceptualization and measurement. In S. Kaiser & M. L. Damhorst (eds.), *Critical Linkages in Textiles and Clothing: Theory, Method and Practice*. Monument, CO: ACPTC.

Brown, L. (1992). A survey of image registration techniques. *ACM Computing Surveys*, *24*(4), 325-376.

Celcar, D., Meinander, H., & Gersak, J. (2008). Heat and moisture transmission properties of clothing systems evaluated by using a sweating thermal manikin under different environmental conditions. *International Journal of Clothing Science and Technology, 20*(4), 240-252.

Contaldo, F., Rocco, P., & Mancini, M. (1980). Left arm thermography in early and maturity onset obesity. *International Journal of Obesity, 4*(1), 43-48.

Desbrun, M., Schroeder, P., & Barr, A. (1999). Interactive animation of structured deformable objects. In *Proceedings of Graphics Interface*, Canadian Computer-Human Communications Society, (pp. 1-8).

Dey, D., Slomka, P. J. Gobbi, D. J., & Peters, T. M. (2000). Mixed reality merging of endoscopic images and 3-D surfaces. *Lecture Notes in Computer Science*. (pgs 796-803). Berlin, DE: Springer.

Durand, F. (2002). Non-photorealistic animation and rendering. In *Proceedings of the 2nd International Symposium on Non-Photorealistic Animation and Rendering* (pgs 111-124), New York, NY: Association for Computing Machinery.

Fan, J., & Cheng, X.-Y. (2005). Heat and moisture transfer with sorption and phase change through clothing assemblies. *Textile Research Journal*, *75*(3), 187-196.

Farnsworth, B. (1986). A numerical model of the combined diffusion of heat and water vapor through clothing. *Textile Research Journal*, *56*(11), 653-665.

Fengzhi, L., & Li, Y. (2005). Effect of clothing material on thermal responses of the human body. *Modeling and Simulation in Materials Science and Engineering*, *13*(6), 809-827.

Ferreira, J. J. A., Mendonca, L. C. S., Nunes, L. A. O., Filho, A. C. C., Rebelatto, J. R., & Salvini, T. F. (2008). Exercise-associated thermographic changes in young and elderly subjects. *Annals of Biomedial Engineering, 36*(8), 1420-1427.

Franken, T., Dellepiane, M., Matteo, G., Fabio, C., Montani, C., & Scopigno, T. (2005). Minimizing user intervention in registering 2D images to 3D models. *Visual Computing*, *21*(8-10), 619-628.

Frim, J., Livingstone, S. D., Reed, L. D., Nolan, R. W., & Limmer, R. E. (1990). Body composition and skin temperature variation. *Journal of Applied Physiology*, *68*(2), 540-543.

Gavin, T. P. (2003). Clothing and thermoregulation during exercise. *Sports Medicine, 33*(13), 941-947.

Goshtasby, A. (2005). *2-D and 3-D image registration for medical, remote sensing, and industrial applications*. Hoboken, NJ: Wiley Interscience.

Holm, I. R. (2006). Protective clothing in hot environments. *Industrial Health, 44,* 404-413.

Han, J. & Bhanu, B. (2005), Real world applications: Hierarchical multi-sensor image registration using evolutionary computation. In *Proceedings of the 2005 Conference on Genetic and Evolutionary Computation GECCO '05* (pgs 2045-2052), Washington, DC: ACM Press.

Hart, J., Omolo, B., & Boone, W. R. (2007). Thermal patterns and health perceptions. *Journal of Canadian Chiropractic Association, 51*(2), 106-111.

Herbert, R. A., & Rowswell, M. (2006). Maintaining body temperature. In S. J. Redfern & F. M. Ross (Eds.), *Nursing older people* (pp. 413-430). Livingstone, New York: Elsevier/Churchill.

Inoue, Y., Nakao, M., Araki, T., & Ueda, H. (1992). Thermoregulatory responses of young and older men to cold exposure. *European Journal of Applied Physiology & Occupational Physiology*, *65*, 492-498.

Istook, C. L. (2000). Rapid prototyping in the textile and apparel industry: A pilot project. *Journal of Textile Apparel, Technology and Management*. *1*(1), 1-14.

Istook, C. L., & Hwang, S. (2001). 3D body scanning systems with application to the apparel industry. *Journal of Fashion Marketing and Management*, *5*(2), 120-132.

Ji, Q., & Hu, R. (2002). 3D face pose estimation and tracking from a monocular camera. *Image and Vision Computing*, *20*(1), 499-511.

Kahn, F., Spence, V. A., & Belch, J. J. (1992). Cutaneous vascular responses and thermoregulation in relation to age. *Clinical Science (London), 82*, 521-528.

Kang, T. J., & Kim, S. M. (2000). Optimized garment pattern generation based on three dimensional anthropometric measurement. *International Journal of Clothing Science and Technology, 12*(4), 240-254.

Kang, Y. M., & Cho, H. G. (2002). Bilayered approximate integration for rapid and plausible animation of virtual cloth with realistic wrinkles. In *Proceedings of Computer Animation*, IEEE Computer Society (203-214).

Kim, S., & Park, C. K. (2007). Basic garment pattern generation using geometric modeling method. *International Journal of Clothing Science and Technology, 19*(1), 7-17.

Kinnicutt, P., Domina, T., MacGillivray, M., & Lerch, T. (2010). Knit-in 3D mapping's effect on thermoregulation: Preliminary results. *Journal of the Textile Research Institute*, *101*(2), 120-127.

Kulka, T. J., & Kenney, L. W. (2005). Heat balance limits in football uniforms. *The Physician and Sports Medicine, 30*(7), 1-8.

Lee, S-E., & Chen, J. C. (2000). Mass-customization methodology for an apparel industry with a future. *Journal of Industrial Technology, 16*, retrieved December 12, 2005 from http://www.nait.org/jit/Articles/leee1222.pdf.

Lerch, T., Anthony, S., & Domina, T. (2008). Preliminary validation of point cloud data from a 3D body scanner. *International Journal of Clothing Science and Technology*, *20*(5), 271-280.

Li, Y., & Holcombe, B. V. (1998). Mathematical simulation of heat and moisture transfer in a human-clothing-environment. *Textile Research Journal*, *68*(6), 389-397.

Loker, S., Ashdown, S. P., & Schoenfelder, K. (2005). Size-specific analysis of body scan data to improve apparel fit. *Journal of Textile and Apparel, Technology and Management*, *43*(3), 1-15.

Loker, S., Cowie, S., Ashdown, S., & VanDyk, L. (2004). Female consumers' reactions to body scanning. *Clothing and Textile Research Journal*. *22*(4), 151-160.

Lu, S-H., & Dai, Y-T. (2009). Normal body temperature and the effects of age, sex, ambient temperature and body mass index on normal oral temperature: A prospective, comparative study. *International Journal of Nursing Studies*, *46*, 661-668.

McCullough, E. A., Jones, B. W., & Huck, J. (1985). A comprehensive data base for estimating clothing insulation. *ASHRAE Transactions, 91*(2A), 29-47.

McKinnon, L., & Istook, C. L. (2002). Body scanning: The effects of subjection respiration and foot positioning on the data integrity of scanned measurements. *Journal of Fashion Marketing and Management*, *6*(2), 103-121.

McKinnon, L., & Istook, C. L. (1999). *Psychological Issues Concerning Body Scanning*. Paper presented at the Annual Meeting of the International Textile and Apparel Association, Santa Fe, NM, 1999.

Niu, H., Lui, P., Hu, J. S., Ting, C., Yin, Y., Lo, Y., Liu, L., & Lee, T. (2001). Thermal symmetry of skin temperature: Normative data of normal subjects in Taiwan. *Chinese Medical Journal, 64*, 459-468.

Olesen, B. W. (1985). A new and simpler method for estimating the thermal insulation of a clothing ensemble. *ASHRAE Transactions*, *91*(2), 478-492.

Owens, E. F., Hart, J. F., Donofrio, J. J., Haralambous, D. C., & Mierzejewski, E. (2004). Paraspinal skin temperature patterns: An interexaminer and intraexaminer reliability study. *Journal of Manipulative and Physiological Therapeutics*, *27*(3), 155-159.

Pascoe, D. D., Shanley, L. A., & Smith, E. W. (1994). Clothing and exercise I: Biophysics of heat transfer between the individual, clothing and the environment. *Sports Medicine*, *18*(1), 38-51.

Passlick-Deetjen, J., & Bedenbender-Stol, E. (2005). Why thermosensing? A primer on thermoregulation. *Nephrology Dialysis Transplant*, *20*, 1784-1789.

Petrova, A., & Ashdown, S. P. (2008). Three-dimensional body scan analysis:

Body size and shape dependence of ease values for pants fit. *Clothing and Textile Research Journal*, *26*(3), 227-252.

Reuters News Agency (6/12/2008). *Lectra: With newly extended Modaris 3D Fit simulation capabilities, Lectra promotes the use of virtual 3D prototyping*. Retrieved from http://www.reuters.com/article/pressRelease/idUS187853+12-Jun-2008+MW20080612

Roy, R., Boucher, J. P., & Comtois, A. S. (2006). Validity of infrared thermal measurements of segmental paraspinal skin surface temperature. *Journal of Manipulative and Physiological Therapeutics*, *29*(2), 150-155.

Salisbury, R. S., Parr, G., De Silva, M., Hazleman, B. L., & Page-Thomas, P. (1983). Heat distribution over normal and abnormal joints: Thermal pattern and quantification. *Annals of the Rheumatic Diseases*, *42*, 494-499.

Savastano, D. M., Gorbach, A. M., Eden, H. S., Brady, S. M., Reynolds, J. C., & Yanovski, J. A. (2009). Adioposity and human regional body temperature. *American Journal of Clinical Nutrition*, *90*, 1124-1131.

Simmons, K. P., & Istook, C. L. (2003). Body measurement techniques: Comparing 3D body-scanning and anthropometric methods for apparel applications. *Journal of Fashion Marketing and Management*. *7*(3), 306-332.

Spalding, S. J., Kwoh, C. K., Boudreau, R., Enama, J., Lunich, J., Huber, D., Denes, L., & Hirsh, R. (2008). Three-dimensional and thermal surface imaging produces reliable measures of joint shape and temperature: A potential tool for quantifying arthritis. *Arthritis Research & Therapy, 10*(1). Available online at: http://arthritis-research.com/content/10/1/R10.

Taffett, G. E. (2003). Physiology of aging. In C. K. Cassel (Ed.), *Geriatric medicine: An evidence-based approach* (pp. 27-35). New York, NY: Springer.

Terzopoulos, D., Platt, J., Barr, A., & Fleischer, K. (1987). Elastically deformable models. *ACM SIGGRAPH Computer Graphics*, *21*(4), 205-214.

Ueda, H., Inoue, Y., Matsudaira, M., Araki, T., & Havenith, G. (2006). Regional microclimate humidity of clothing during light work as a result of the interaction between local sweat production and ventilation. *International Journal of Clothing Science and Technology, 18*(4), 225-234.

Voelker, C., Hoffmann, S., Kornadt, O., Arens, E., Zhang, H., & Huizenga, C. (2009). Heat and moisture transfer through clothing. In *Proceedings of the Eleventh International IBPSA Conference*, (pp. 1360-13366), Glasgow, UK.

Volino, P., Davy, P., Bonanni, U., Luible, C., Magnenat-Thalmann, N., Makinen, M., & Meinander, H. (2007). From measured physical parameters to the haptic feeling of fabric. *Visual Computer, 23*(2), 133-142.

Volino, P., & Magnenat-Thalmann, N. (2005). Accurate garment prototyping and simulation. *Computer-Aided Design, 2*, 645-654.

Wagner, J. A., Robinson, S., & Marino, R. P. (1974). Age and temperature regulation of humans in neutral and cold environments. *Journal of Applied Physiology, 37*, 562-565.

Watkins, S. (1995). Clothing: The portable environment. Ames, IA: Iowa State University Press.

Wissler, E. H., & Havenith, G. (2009). A simple theoretical model of heat and moisture transport in multi-layer garments in cool ambient air. *European Journal of Applied Physiology*, *105*(5), 797-808.

Wong, A. S. W., Li, Y., & Yeung, K. W. (2002). Statistical simulation of psychological perception of sensory clothing comfort. *Journal of the Textile Institute*, *93*(1), 108-119.

Xu, B., Huang, Y., Yu, W., & Chan, T. (2002). Three-dimensional body scanning system for apparel mass customization. *Optical Engineering*. *41*, 1475-79.

Yi, L., Aihua, M., Ruomei, W., Xiaonan, L., Zhong, W., Wenbang, H. Liya, Z., & Yubei, L. (2006). P-smart: A virtual system for clothing thermal functional design. *Computer-Aided Design, 38,* 726-739.

Yokota, M., & Bathalon, G. (2008). Effects of female anthropometric variability on simulated thermal responses. *Aviation, Space, and Environmental Medicine*, *79*(3), 254.

Yoo, S., & Barker, R. L. (2005). Comfort properties of heat resistant protective workwear in varying conditions of physical activity and environment. Part I: Thermophysical and sensorial properties of fabrics. *Textile Research Journal*, *75*(7), 523-530.

Zhong, Y., & Xu, B. (2009). Three-dimensional garment dressing simulation. *Textile Research Journal*, *79*(9), 792-803.