JINHEE NAM *Ball State University*

DONNA H. BRANSON* *Oklahoma State University*

SUSAN P. ASHDOWN** *Cornell University*

HUANTIAN CAO*** *University of Delaware*

ERICA CARNRITE**** *Cornell University*

Analysis of Cross Sectional Ease Values for Fit Analysis from 3D Body Scan Data Taken in Working Positions

Purpose- The purpose of this study was to compare the fit of two prototype liquid cooled vests using a 3D body scanner and accompanying software. The objectives of this study were to obtain quantitative measurements of ease values, and to use these data to evaluate the fit of two cooling vests in active positions and to develop methodological protocol to resolve alignment issues between the scans using software designed for the alignment of 3D objects.
Design/methodology/approach- Garment treatments and body positions were two independent variables with three levels each. Quantitative dataset were dependent variables, and were manipulated in 3x3 factorial designs with repeated measures. Scan images from eight subjects were used and ease values were obtained to compare the fit. Two different types of analyses were conducted in order to compare the fit using t-test; those were radial mean distance value analysis and radial distance distribution rate analysis.
Findings- Overall prototype II achieved a closer fit than prototype I with both analyses. These were consistent results with findings from a previous study that used a different approach for evaluation.
Research limitations/implications- The main findings can be used as practical feedback for prototype modification/ selection in the design process, making use of 3D body scanner as an evaluation tool.
Originality/value- Methodological protocols that were devised to eliminate potential sources of errors can contribute to application of data from 3D body scanners.

Assistant professor, Department of Family & Consumer Sciences, Ball State University, Muncie, Indiana (jnam@bsu.edu)

*Regents professor & Emeritus, Department of Design, Housing & Merchandising, Oklahoma State University, Stillwater, Oklahoma

**Professor, Department of Fiber Science & Apparel Design, Cornell University, Ithaca, New York

***Associate professor, Department of Fashion & Apparel Studies, University of Delaware, Newark, Delaware

****Research assistant, Cornell University, Ithaca, New York

Key Words: *Garment Ease, Fit analysis, 3D body scanner, Cooling Vest, Ease Value*

First responders are required to wear personal protective equipment (PPE) for protection from exposure to hazardous materials and hostile environments. Highly impermeable PPE and heavy auxiliary equipment that the first responders carry increase the thermal stress experienced by the first responders. Personal cooling systems have been shown to play a critical role in reducing the heat burden in these conditions (Nunley, 1970; Crockford and Lee, 1967; Duncan and Konz, 1975). A liquid cooled vest with an embedded tubing system that cools using chilled water can decrease body temperature significantly through conduction. To increase cooling efficiency, a close fitting liquid cooled garment is a pre-requisite. However, achieving a comfortable close fit for many different individuals is a particularly challenging problem with standard sized garments. Kurt Salmon Associates reported that 62 percent of U.S. consumers are very dissatisfied with the fit of their apparel (Kurt Salmon Associates, 1999). Recently the three-dimensional body scanner has proven to be a useful tool in research designed to improve the fit of ready-to-wear apparel (Ashdown *et al.*, 2004).

Use of the 3D Body Scanner in the Apparel Industry

The 3D body scanner has been utilized by the apparel industry primarily for collecting body measurement data. Using a 3D body scanner to collect anthropometric data on individuals is easier and faster than traditional methods using tape measures and calipers. Istook and Hwang (2001) listed speed, accuracy, reproducibility of the data, and availability of new or revised measurement extraction at any time as advantages. For example, it required four hours physically to landmark, measure and record the data of one subject by traditional methods in a 1988 anthropometric survey of US Army personnel (Paquette, 1996). Many national body measurement surveys including SizeUSA and CAESAR study have been completed using 3D body scan technology with the goal of obtaining a database to build new sizing systems relevant for the current population ([TC] ^{2} , SAE International, nd).

Much research is going on in the area of integrating body-scan and apparel CAD technologies. Loker *et al.*, (2004) reported the potential use of the body scanner as the development of automated custom fit, size and fit prediction, virtual try-on, personal shopper services, co-design mass customization, custom pattern development for home sewers, and apparel research studies. Scan data can also be used for the creation of dress forms that replicate an apparel company's fit model (Loker *et al.*, 2004).

The 3D body scanner also has been used to solve design problems in specialized apparel areas. In a study of methods for reducing the heat burden in protective clothing a thermal manikin was dressed in protective gear and the space between the manikin and protective gear was measured to assess the effect of air layers on heat loss (Deaton and Barker, 2004). Lee *et al.*, (2006) examined potential sun protection afforded by various styles of brimmed head wear in specified positions using a 3D body scanner.

Quantitative Fit Analysis and Related Issues using the 3D Body Scanner

Analysis of the fit of clothing is a complex process of assessing the relationship between the human body and clothing and by judging how well the clothing conforms to a set of fit requirements (Ashdown *et al.*, 2004). Work is underway to make mathematical comparisons of measurements from 3D body scans, transferring existing industrial techniques to improve apparel fit (Loker *et al.*, 2005; Tahan *et al.*, 2003).

Quantitative analysis of optimized ease has been investigated by several researchers (Meunier *et al*, 2000; Kim *et al.*, 2001). Ease can be described as a fit indicator representing the difference between measurements of the skin surface and the garment. Since current 3D body scanners capture only surface data of an object, special protocols have been developed to assess ease.

Meunier *et al.* (2000) devised a method to assess helmet fit using a 3D body scanner. Standoff distances, the distance between the inside of the helmet surface and the head surface was used as a fit indicator, that was, ease. First, the helmet was scanned on the subject's head, followed by a scan of the subject's head with a latex swim cap to compress the hair against the head. The helmet scan was then offset by the thickness of the helmet, to obtain a representation of the inside surface of the helmet. Comparisons were then made between this representation of the inner surface and the scan of the head surface to acquire standoff values.

Kim *et al.*, (2001) also compared and evaluated the wearing ease of a ready-to-wear jacket using a 3D body scanner. Cross sections from body scans and scans of the same subjects wearing the jackets in identical position were layered using an AutoCAD program. The relationship between the cross section of the body and that of the clothed body showed the wearing ease of the jacket at each cross section location.

Several methodological issues in the use of body scanners for ease analysis have the potential to cause errors and need to be resolved by researchers. In order to be able to compare the space between test clothing and the subject's body, two separate scans must be taken, and the scan image of the test garment and the scan image of the body would ideally be precisely aligned. However it is challenging for subjects to achieve an identical posture for each scan. Kim *et al.*, (2001) told their subjects to set their feet apart about 20 cm wide and to lift their arms to 30° angle in an effort to maintain the same standing position.

This study was designed to compare the fit of two prototype liquid cooled vests using a 3D body scanner and accompanying software. Various techniques were used to quantify fit from the radial distances.

The objectives of the study were 1) to obtain a quantitative measurement of ease values, and 2) to use these data to evaluate the fit of two cooling vests in standing, bending and twisting positions. In order to accomplish these objectives it was necessary to resolve alignment issues between the scans, which were more problematic in active positions, using software designed for the alignment of 3D objects. Methods to minimize errors inherent in 3D measurement processes that can contribute to inaccurate data were also employed.

METHODOLOGY

Subjects

Thirteen volunteers were recruited as a convenience sample from a local area fire station and the life safety department of a university located in the northeast. Among the data of thirteen volunteers,

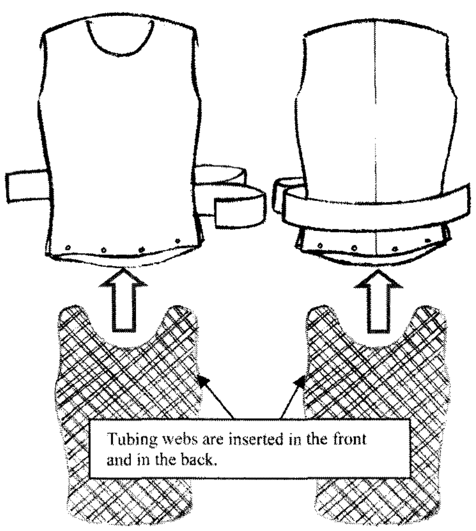
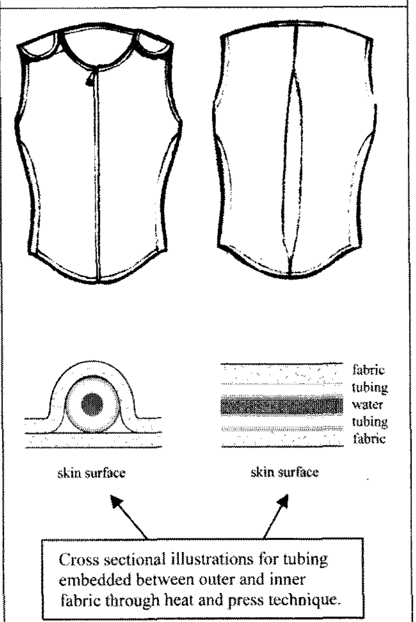
	Prototype I	Prototype II
Illustrations	 Note: Prototype I consists of two layers of fabric, an outer layer and a lining layer, with tubing webs for cooling inserted between the layers.	
Fabrication and Cooling mechanism	A tubing web for cooling is inserted and hangs free between the layers. Knitted fabrics were used for both fabric layers to fit various body shapes in the same size range. Conceptual prototype.	Tubing was embedded into the fabric using a heat and bonding technique, creating a stiffer fabrication. Stretch panels were inserted into side and back for better fitting.

Figure 1. *Prototype I and II Illustrations*

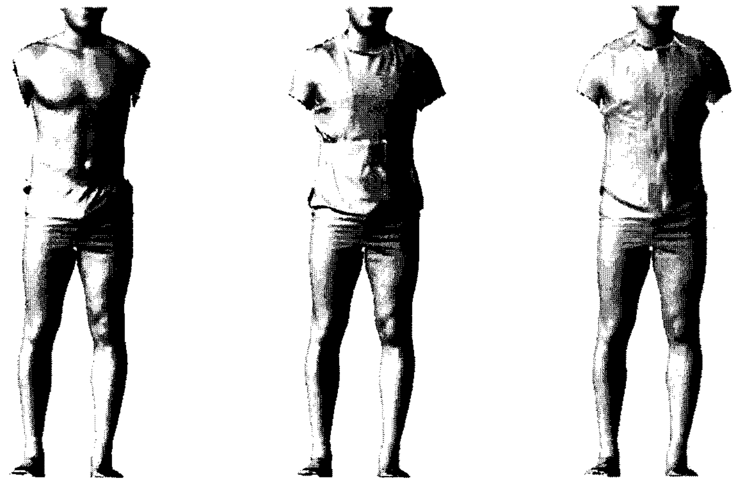


Figure 2. *Minimally Clothed, Prototype I & II in Standing Position*

only the data from 8 subjects met the designated sizing criteria for the prototype vests and were used in this analysis.

Independent Variables

The garment treatment and body position, each with three levels, were manipulated in a 3x3 factorial design with repeated measures.

The three levels of garment treatment consisted of minimally clothed, prototype I and prototype II. The minimally clothed scan image was required to capture a body image for the measurement of the ease between the body and garment. The prototypes were two liquid cooled garment systems designed by the Oklahoma State University National Memorial Institute for the Prevention of Terrorism (MIPT) project team as a part of a large 3-year study for the development of a portable personal cooling system for first responders wearing Personal Protective Equipment (PPE). Both prototypes used the same fabric and tubing but the design of the prototypes and the attachment techniques between fabric and tubing were quite different. Prototype I was a pullover style vest designed to maximize adjustability and flexibility while maintaining skin contact having tubing webs in a diagonal pattern between two layers of fabrics. Prototype II had a front zipper closure and the tubing was bonded to the inner and outer fabric layers using heat and an adhesive, forming a sandwich construction (Nam *et al.*, 2005, presented in Fig. 1).

Fig. 2 shows examples of minimally clothed, prototype I, and prototype II scan images, in the standing position. Three body positions, standing, bending and twisting positions were selected as representative of positions that first responders might assume while performing their work. These positions can be seen in Fig. 3.

Dependent Variables

The difference data set between the inner surface of the liquid cooled vest and the surface of the body, a measure of ease values, was measured and analyzed in a quantitative way to evaluate and compare fit.

Methods and Procedures

The basic concept was to measure the cross sectional distances between the inner surface of the liquid cooled vests and the surface of the subject's skin at multiple body areas. In order to do this, close alignment of each subject's scans in the standing and the working poses is desired. Subjects were instructed to place their feet and to grasp positioning bars in identical places for each repeated scan of the active positions to minimize misalignment.

To align the resulting scans for each subject and

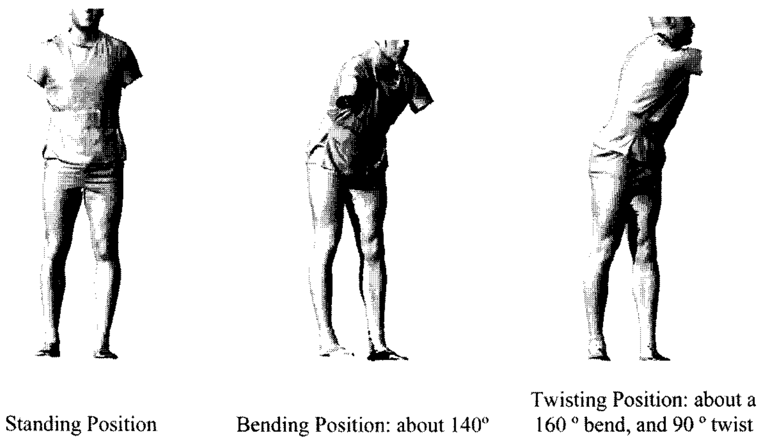


Figure 3. *Three Body Positions*

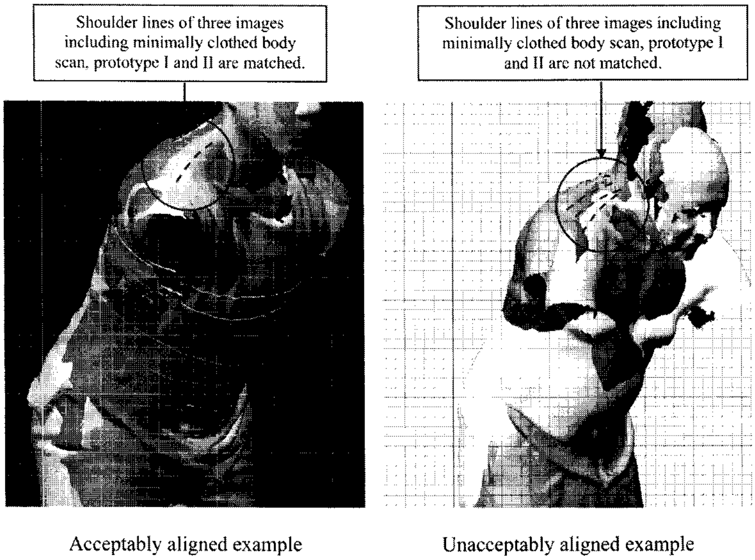
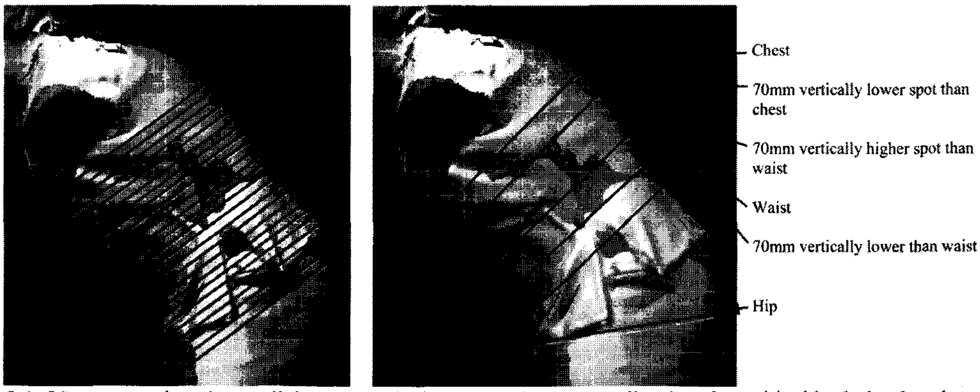


Figure 4. *Example of Acceptably and Unacceptably Aligned Images*

position, the researcher first removed the arms from the scan, so that the torso areas of the scans were not obscured. The 3D images (the image of minimally clothed, prototype I and prototype II) for each subject/position combination were then brought onto the computer screen simultaneously and aligned with one another using Polyworks IMInspect, a software designed to align multiple 3D images automatically by finding the position with the least variation among the scans. Then the image alignment was refined manually by rotating and translating the 3D images until they were visually aligned as much as possible. For 21 of the 24 sets of merged scans (8 subjects x 3 positions) the body, prototype I, and prototype II scans were successfully aligned. Three sets of scans could not be aligned properly due to variations and were eliminated from further analysis. Fig. 4 shows an example of acceptably and unacceptably aligned sets of three images merged on the computer screen.

After aligning the three images, 31 cross sections were created in the torso section of each scan. These cross sections were aligned with the central axis of the torso in each case, and they were positioned identically for the three scans of each of the participant/position scan sets. Data could only be



5-1. 25 cross sections in parallel 5-2. 6 cross sections manually placed at critical body landmarks

Figure 5. *Cross Sections Generated for Each Subject in Each Position*

collected from areas of the body where a full circumference could be obtained, so cross sections were not taken above the armhole area where there were missing areas of the scan.

Twenty-five of the 31 cross sections were created by dividing the distance from the underarm to the hip into 24 equal intervals, at right angles to the central torso axis (Fig. 5.1). These cross sections were used to determine the radial distance measurement between the skin surface and the inner prototype vest surface.

Six additional cross sections were created manually for a comparison of the ease at body landmarks critical to fit. The six critical body landmarks chosen by the researcher included the chest, waist, hip, 70 mm below the chest, 70 mm above the waist, and 70 mm below the waist (Fig. 5. 2).

Once cross sections were created, the alignment of each set of cross sections was further refined using an error compensation function. The error compensation function is an automated search function that locates the shortest distance between points of the sets of cross sections from the body scan and the vest scans. When the angle between points is too great the match is rejected. This happens in cases where there are not enough data points on a cross section to provide a direct radial measure from one cross section to the other. The cross sections created without error compensation were eliminated from this study.

The next step in the process was to apply an offset function to the vest cross sections to compensate for the vest thicknesses. Vest thickness was an issue because the scan data are captured from the outside surface of the vest, but the inside surface of the vest as it interacts with the body is the point of interest in this research. The offset function in the IM Alignment software was used to adjust the vest thickness, and it was used to automatically subtract the appropriate thickness value from each prototype slice. The average thickness of each prototype was identified as the offset value, which was 5.12 mm for prototype I, and 3.14 mm for prototype II. For prototype I, the tubing was woven, so two layers of tubing crossed at each intersection, while a single layer of tubing was embedded using heat sealed adhesives for prototype II, thus these different techniques caused different vest thickness. Fig. 6 shows an example of a set of the three cross sections of the waist area of one of the subjects in all three positions.

Data Analysis

Radial mean distance analysis Once the cross sections were prepared the radial distances between the offset value of each prototype cross section and the corresponding body cross section were measured and compared to assess the fit characteristics of each prototype (Fig. 7). Measurements were taken at each point around the cross section where there were data points from the scan. The numbers of data points varies depending on the size of the circumference. The radial distance values of each set of data points were averaged as a measure of the overall tightness

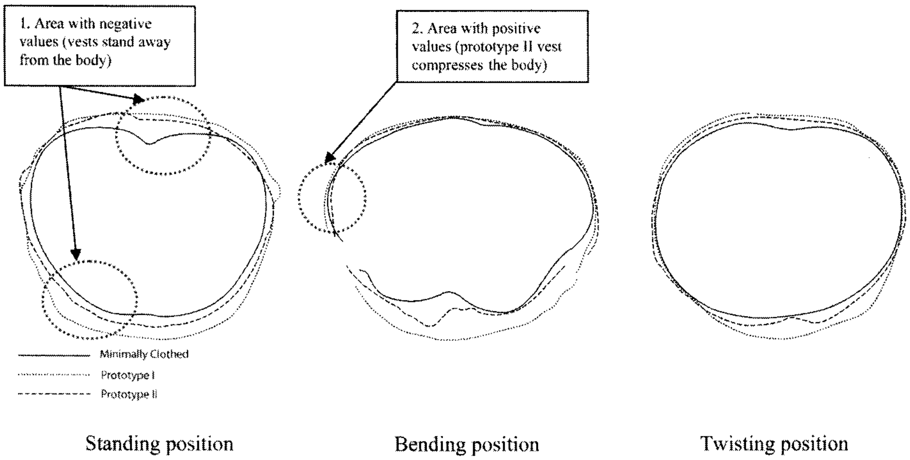
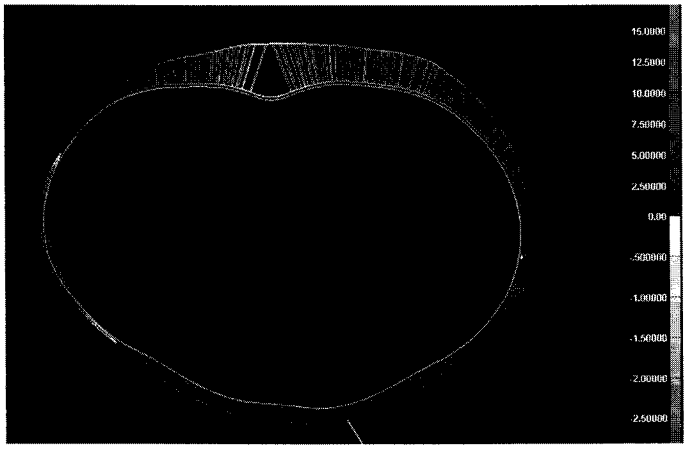


Figure 6. *Areas in Cross Section with Positive and Negative Values (Slices Taken in the Standing, Bending and Twisting Position at 70 mm below the Chest)*



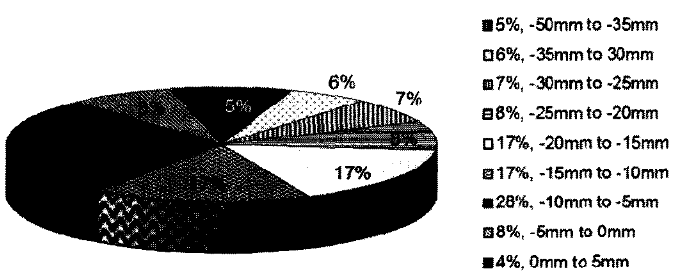
Note: The distance between the different surface layers were calculated and presented as a color spectrum
Figure 7. Example of Radial Measurements between the Body and Prototype Cross Sections Taken at the Waist in the Standing Position

of the fit at each cross section area. The radial mean distance values of the 25 cross sections were used for overall fit evaluation, and the radial mean distance values of the six critical body landmarks were used to see the fit at each body landmark.

Since the prototypes were designed with the goal of providing a very close fit, many of the cross sections had areas where the body cross sections, unconfined in the scans of the minimally clothed state, crossed over the cross sections of the prototypes, in which areas of the body were compressed. This resulted in both positive and negative radial values from many of the cross sections. In this study, the negative values are radial measures for which the prototype cross sections are larger than the body cross sections, as radial measures always originated with the cross sections for the prototype. This is different from the general concept that negative ease means compression. Fig. 6 shows a set of 70 mm below the chest cross sections taken in standing, bending and twisting positions with areas of both positive and negative values.

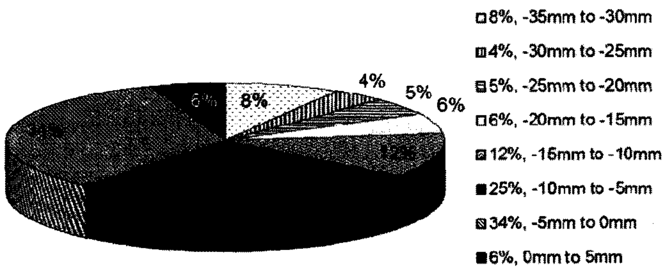
Radial distance distribution analysis Besides radial

Cross Sections Pie Chart (Prototype I)



Note: Data from -50mm to -35mm combined into one category.

Cross Sections Pie Chart (Prototype II)



Note: Negative distance value indicates the vest cross section is larger than the body cross section. The negative values closer to zero indicate smaller ease values.

Figure 8. Pie Chart and Table of the Categorized Radial Distance Distribution Rate Values from a Subject's Chest Cross Sections at the Chest in a Bending Position

mean distance values, the number and percent of radial measures were counted in 5mm categories for each cross section at six critical body landmarks for each prototype in different positions. Fig. 8 presents the radial mean distance distribution rate of chest cross sections for a subject in prototypes I and II calculated as percentages of radial measures categorized at 5 mm increments. This shows that four percent of the radial distances were between 0 mm and 5 mm for prototype I, and six percent of the radial distances were between 0 mm and 5 mm for prototype II. Prototype I had more widely distributed ranges than prototype II, and had a large percentage of radial distance measurement points in the -35 mm to -15 mm ranges. This meant that prototype I gapped away from the body more than prototype II. Prototype II fitted closer to the body than prototype I at this cross section location with 77 % of the radial measurements between -15 mm and 5 mm. Only 57% of prototype I radial measures were in the -15 mm to 5 mm category.

Since a close fit was desired in this study, the range of radial measures from -10 mm to 10 mm was determined as the preferred distance range providing close as well as comfortable fit. Each percentage value of the radial mean distance distribution rate at each 5 mm interval category between -10 mm to 10 mm was summed up, and the mean value of 8 subjects was compared across the two prototypes.

RESULTS

Comparison of Overall Radial Mean Distance of Prototype I and II through 31 Selected Body Areas

All of the mean values, representing mean ease, of the 25 cross sections that were created at equal

Table 1. *T-test Result: Comparison of Overall Mean Distance in mm of 8 Subjects Between Prototype I and II at Each Position*

Position	Prototype	N	M	SD	t	p
Standing Position	Prototype I	7	-14.67 mm	1.34	-4.921	0.00**
	Prototype II	7	-9.82 mm	2.24		
Bending Position	Prototype I	7	-14.50 mm	1.64	-3.33	0.01**
	Prototype II	7	-9.88 mm	3.27		
Twisting Position	Prototype I	7	-13.54 mm	1.64	-3.67	0.00**
	Prototype II	7	-9.73 mm	2.29		

The prototype which achieved tighter fit is marked in bold type.
$*p \le 0.05$, $**p \le 0.01$
Note: Negative value indicates the vest cross section is larger than the body cross section. The negative values closer to zero indicate smaller ease values.

Table 2. *T-test Results of Distance Mean Comparisons in mm Between Prototype I and II in the Three Active Positions*

		Prototype I (mm)			Prototype II			t	p
		N	Mean	SD	N	Mean	SD		
Standing Position	Chest area	7	-14.77	3.01	7	**-7.71**	3.38	-4.13	0.001**
	Chest-70 mm	7	-20.57	2.37	7	**-10.86**	2.80	-7.01	0.00**
	Waist+70 mm	7	-14.65	3.47	7	**-11.42**	2.85	-1.90	0.81
	Waist	6	-11.43	4.52	7	**-10.57**	3.84	-3.29	0.75
	Waist-70 mm	7	-15.43	5.51	7	**-12.98**	5.21	-8.55	0.41
	Hip	6	-10.22	4.36	7	**-5.36**	2.80	-2.44	0.03*
Bending Position	Chest area	7	-18.78	3.43	6	**-9.57**	2.40	-5.51	0.00**
	Chest-70 mm	7	-21.01	2.30	5	**-12.31**	2.09	-6.70	0.00**
	Waist+70 mm	7	-12.07	5.95	6	**-11.53**	1.54	-0.21	0.84
	Waist	6	**-10.53**	2.99	6	**-12.63**	3.19	1.18	0.27
	Waist-70 mm	6	-15.45	5.64	6	**-12.42**	6.16	-0.89	0.40
	Hip	7	-12.70	2.68	7	**-5.33**	4.10	-3.98	0.02
Twisting Position	Chest area	7	-14.08	1.66	7	**-9.82**	2.94	-3.33	0.01*
	Chest-70 mm	7	-17.24	2.18	7	**-11.23**	3.83	-3.61	0.01*
	Waist+70 mm	7	-12.07	4.41	7	**-11.17**	3.53	-0.42	0.68
	Waist	7	-13.23	3.25	7	**-11.60**	4.18	-0.82	0.43
	Waist-70 mm	6	-17.63	2.88	7	**-11.95**	3.92	-0.87	0.13*
	Hip	7	-8.87	1.89	7	**-3.96**	1.32	-5.62	0.00**

The prototype which achieved tighter fit is marked in bold type.
$*p \le 0.05$, $**p \le 0.01$
Note: Negative value indicates the vest cross section is larger than the body cross section. The negative values closer to zero indicate smaller ease values

intervals, were summed and averaged for each prototype and at each position to represent overall fit in the torso area.

The mean differences of the 8 subjects were analyzed using an independent t-test, and the result indicated that there were significant differences in mean distances between prototypes at each of the three garment positions (Table 1). Based on these mean values, prototype II achieved a closer fit than prototype I for all subjects in all three positions (standing, bending and twisting position).

Comparison of Radial Mean Distances of Prototypes I and II at Six Selected Body Areas

To examine the closeness of fitting at each of the manually created six cross sections from the three

Table 3. *Comparison between Prototype I and II of the Percentage of Radial Distances between the Values of 10 mm and -10 mm from Slices at Critical Fitting Points in Each Body Position*

		Prototype I (%)			Prototype II (%)			t	p
		N	Mean of 4 Best Fit Categories***	SD	N	Mean of 4 Best Fit Categories***	SD		
Standing Position	Chest Area	6	12.29	13.44	6	**36.15**	16.37	-2.58	0.028*
	Chest-70 mm	6	3.46	8.20	6	**23.40**	13.60	-4.91	0.001**
	Waist+70 mm	6	0.00	23.48	6	**27.50**	16.48	-1.82	0.098
	Waist	6	17.21	23.84	6	**33.52**	20.38	-1.12	0.290
	Waist-70 mm	6	9.71	17.47	6	**11.74**	32.13	-0.57	0.580
	Hip	6	34.92	17.77	6	**65.94**	13.92	-2.56	0.028*
Bending Position	Chest area	7	25.98	5.47	7	**41.26**	9.72	-5.81	0.000**
	Chest-70 mm	7	1.27	13.50	7	**30.07**	13.15	-3.75	0.003**
	Waist+70 mm	7	8.31	28.98	7	**35.92**	18.40	-0.31	0.764
	Waist	7	23.74	24.45	7	**28.34**	21.41	-0.32	0.758
	Waist-70 mm	7	7.48	14.70	7	**11.40**	31.23	-1.66	0.123
	Hip	7	2.28	21.47	7	**63.55**	10.42	-3.91	0.002**
Twisting Position	Chest area	6	18.29	11.16	6	**24.47**	19.99	-2.40	0.037
	Chest-70 mm	6	10.05	8.68	6	**30.00**	18.21	-4.00	0.003**
	Waist+70 mm	6	2.51	24.37	6	**21.45**	18.64	-0.42	0.682
	Waist	6	23.74	10.34	6	**21.10**	17.61	-1.51	0.161
	Waist-70 mm	6	11.14	8.97	6	**27.89**	11.57	-3.13	0.011
	Hip	6	30.88	13.02	6	**29.82**	24.70	-2.71	0.022

The mean value which indicates tighter fit is marked in bold type.
*$p \leq 0.05$, **$p \leq 0.01$
*** -5 mm to -10 mm, 0 mm to 5 mm, 0mm to 5 mm, and 5 mm to 10 mm

different positions, the radial mean distances from these cross sections for prototype I and II were compared using t-tests.

The descriptive statistics indicated that the prototype II fit more closely than prototype I at all six body landmarks in the three different body positions except the waist area in the bending position. The waist belt of prototype I might account for this difference. This result is similar to previous results from visual analysis of the same scans (Nam *et al*, 2005). Significant differences between prototype I and II were found at chest ($p \leq 0.01$), 70 mm below the chest ($p \leq 0.01$), and hip areas ($p \leq 0.05$) in standing position, chest ($p \leq 0.01$) and 70 mm below the chest ($p \leq 0.01$) areas in bending position, chest ($p \leq 0.05$), 70 mm below the chest ($p \leq 0.05$), 70 mm below the waist ($p \leq 0.05$) and hip areas ($p \leq 0.01$)in twisting position from the t-test (Table 2).

Comparison of Radial Distance Distribution Rate of Prototype I and II at Six Selected Body Areas

To examine the closeness of fitting at each of the manually created six cross sections from the three different positions, the radial distance distribution rate from these cross sections for prototype I and II were compared using t-tests. Specifically, the four percentage categories that represent best fit defined as values between -10 mm and 10 mm in 5 mm increments (i.e. -10 to -5, -5 to 0, 0 to 5, and 5 to 10) were averaged among the participants for each of the slices taken at the critical fitting points. These averages representing different distribution rates are compared in Table 3 for each of the body positions. The fit as defined by this distribution was significantly better in the chest area and hip for standing and bending positions, and significantly better at the full chest for the twisting position

The descriptive statistics indicated that prototype II achieved closer fit than prototype I at all six body landmark cross sections in three different body positions. Especially, significant differences were found at the chest ($p \leq 0.05$), 70 mm below the chest ($p \leq 0.01$), and hip ($p \leq 0.05$) areas in standing position, chest ($p \leq 0.01$), 70 mm below the chest ($p \leq 0.01$), and hip ($p \leq 0.01$) areas in bending position, 70mm below the chest ($p \leq 0.01$) in twisting position. The t-test results are presented in Table 3.

CONCLUSIONS AND IMPLICATIONS

Three dimensional body scanners make it possible to measure garment ease in new ways to evaluate fit quantitatively and objectively. In the comparison of the two prototypes for this study, direct measures of fit were made to provide data for one of the critical criteria to evaluate the performance of the cooling capacity of the cooling vests. Wearing comfort is also an important criterion, and was evaluated in a previous study. Excessive compression issues were not found in results from wear tests of the prototypes (Nam *et al.*, 2005).

Several methodological techniques were used to generate more reliable data from the multiple body scans and to reduce the source of errors. The potential sources of error in this study would be: 1) mis-alignment between the body scan and the vest scans, 2) inaccurate offset between the scanned surface and the inner surface of the prototypes, and 3) missing data from scan images that could result in radial measures taken at too steep an angle resulting in incorrect values in the calculation process. To eliminate the sources of errors, 1) both automatic alignment software and manual alignment techniques were used to achieve a more accurate and reliable alignment of the images, 2) an offset function was used to subtract the thickness of the fabrication with embedded tubing to approximate the inner surface of the vest accurately, and 3) an error compensation function was used to identify radial measures to be eliminated that were taken at too steep an angle due to missing data. This function made it possible to calculate ease without manually patching the missing areas of the scan, a highly time intensive process.

The t-test results of radial mean distance from the 25 cross sections in parallel showed significant differences between Prototype I and II for all subjects in all three positions, with prototype II achieving closer fit than prototype I. The t-test results of radial mean distance from the six cross sections based on body landmarks showed that prototype II achieved closer fit than prototype I at all six body areas in the standing and twisting positions, with statistically significant differences at the chest area, 70mm below the chest area and at the hip area. For the twisting position the difference 70mm below the waist was also statistically significant. For the bending position, the prototype II fit was tighter than the prototype I fit except at the waist area, where prototype I was tighter. The waist belt of prototype I might be the source of this tightness. Significant differences were found at the chest, 70 mm below the chest and at the hip.

The radial distance distribution rate was also analyzed, and a comparison of descriptive statistics of the portion of the radial measures between -10 mm and 10 mm showed that prototype II achieved closer fit than prototype I at all six body areas in all three active positions. Significant differences were found at the chest, 70 mm below the chest in standing position, chest and 70 mm below the chest and hip in bending position, and 70 mm below the chest in twisting position.

Overall, there were quite consistent results between radial distance analysis and radial distance distribution analysis with one exception. For the both of the analyses, prototype II achieved closer fit than prototype I at all six critical body landmarks in three different positions, except that prototype I achieved a tighter fit at waist in the bending position as calculated from radial distance analysis even though there was no significant difference found.

This quantitative analysis of ease values showed consistent results with a previous study judging the fit of these prototypes from the same scan images based on a visual fit evaluation made by an expert panel (Nam *et al.*, 2005). For both of the studies, prototype II showed closer fit than prototype I, except for the waist fit when the subjects were in the bending position in which prototype I achieved closer fit. However differences between the mean values in the waist area were generally very small ranging from about 1 to 3 mm and were not statistically significant, so the actual fit of prototype I at the waist would be essentially the same as prototype II at the waist. These results show that prototype II achieved good fit even though it used a three layered composite construction in which tubing and fabrics were attached using an adhesive and a heat press method.

ACKNOWLEDGEMENT

This research was supported under Award MIPT-106-113-2000-021 from the National Memorial Institute for the Prevention of Terrorism (MIPT), previously through the National Institute of Justice, and through the Department of Homeland Security and the Oklahoma State University Agricultural Experiment Station (AES).

REFERENCES

Ashdown, S. P., Loker., S., Schoenfelder, K., & Lyman-Clarke, L. (2004). Using 3D scans for fit analysis. *Journal of Textile and Apparel, Technology, and Management*, [Online]. 4(1), Available at: http://www.tx.ncsu.edu/jtatm/volume4issue1/articles/Loker/Loker_full_103_04.pdf (accessed 1 August 2006).

SAE International. (nd). CAESAR: The most comprehensive source for body measurement data (online). Available at: http://www.sae.org/technicalcommittees/caesarhome.htm (assessed 20 June 2011).

Crockford, G. M., & Lee, D. E. (1967). Heat-protective ventilated jackets: A comparison of humid and dry ventilating air. *British Journal of Medicine, 24*, 52-59.

Deaton. A. S., & Barker. R. L. (2004, January). The effect of air layers on heat loss through protective clothing systems. Eighth ASTM Symposium on the Performance of Protective Clothing: Global Needs and Emerging Markets, Tampa, FL.

Duncan, J., & Konz, S. (1975). Design and evaluation of a personal dry-ice cooling jacket. *Human Factors Society*, 359-363.

Kurt Salmon Associates (1999). Annual Consumer Outlook Survey. Kurt Salmon Associates, Atlanta, GA.

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

Kim, H., Suh, C., Suk, E., Park, S., & Lim, J. (2001). A study of the comparative evaluation of wearing fitness of women's ready-made jackets using 3D scanner, *Journal of the Korean Society of Clothing and Textiles*, *25*(10), 1707-1718.

Lee, Y. A., Ashdown, S. P., & Slocum, A. C. (2006). Measurement of surface area of 3-D body scans to assess the effectiveness of hats for sun protection, *Family and Consumer Sciences Research Journal*, *34*(4), 366-385.

Loker, S., Ashdown, S. P., Cowie, L., & Schoenfelder, K. (2004). Consumer interest in commercial applications of body scan data, *Journal of Textile and Apparel Technology and Management*, [Online], 4 (1), Available at: http://www.tx.ncsu.edu/jtatm/volume4issue1/articles/Loker/Loker_full_100_04.pdf (accessed 20 June 2011).

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*, [Online], 4 (3), Available at: http://www.tx.ncsu.edu/jtatm/volume4issue3/articles/Loker/Loker_full_136_05.pdf (accessed 20 June 2011).

Meunier, P., Tack, D., Ricci, A., Bossi, L., & Angel, H. (2000). Helmet accommodation analysis using 3D laser scanning, *Applied Ergonomics*, 3(4), 361-369.

Nam J., Branson D., Ashdown S. P., Cao H., Jin B., Peksoz S., & Farr C. (2005). Fit analysis of liquid cooled vest prototypes using 3D body scanning technology, Journal of Textile and Apparel Technology and *Management*, [Online]. 4(3), Available at: http://www.tx.ncsu.edu/jtatm/volume4issue3/articles/Nam/Nam_full_138_05.pdf (accessed 20 June 2011).

Nunley, S. (1970). Water cooled garments: A Review, *Space Life Sciences*, *2*, 335-360.

Paquette, S. (1996, September). 3D scanning in apparel design and human engineering, *IEEE Computer Graphics and Applications*, *16*(5), 11-15.

Tahan, A., Buxton, B., Ruiz, M. C., & Bougourd, J. (2003, April). Point distribution models of human body shape from a canonical representation of 3D scan data. Paper presented at the Numé risation 3D-Scanning, 3D Human Digitizing and Modelling, UIC, Paris, France.

[TC] 2 (n.d.), *The US National Size Survey*, [Online]. Available at: http://www.sizeusa.com (accessed 20 June 2011).

Received February 5, 2011
Revised June 14, 2011
Accepted June 14, 2011