APPLICATION OF MODEL-CONTROLLED MANIKIN TO PREDICT HUMAN PHYSIOLOGICAL RESPONSE IN FIREFIGHTER TURNOUT GEAR

Richard Burke(1)*, Keith Blood*(1)*, A. Shawn Deaton*(2))*, Dr. Roger Barker*(2)

(1) Measurement Technology Northwest, 4211 24th Avenue West, Seattle, WA 98199
(2) Textile Protection and Comfort Center (TPACC), North Carolina State University
2401 Research Dr. Campus Box 8301, Raleigh, NC 276

Contact person: rick@mtnw-usa.com

INTRODUCTION

Thermal manikins can never and should never completely replace human subject testing. However, the high cost plus inter- and intra- subject variation inherent in testing with humans dictates that a properly designed measurement tool can be an asset to product development and testing. Recent and ongoing studies[1,2] have validated the performance of the Newton thermal manikin operating under control of a physiological control (adaptive manikin system) against pure simulation studies, and historical human subject experiments.

A feasibility study was undertaken at North Carolina State University, Textile Protective and Comfort Center (TPACC) using an adaptive manikin to mimic previous human subject experiments with firefighter turnout gear. The intent of this study was to establish test protocols and viability of using an adaptive manikin system to simulate human physiological response.

METHODS

The 34 zone thermal manikin “Newton” (Measurement Technology Northwest, Inc) with sweating, walking, and breathing functions was coupled to the “ManikinPC^2” software package to create a dynamic and adaptive system. The manikin provides the boundary layer interface to the clothing and environment and generates metabolic heating levels as requested by the regulation model. ManikinPC^2 regulation software is adapted from the RadTherm finite difference thermal analysis program (ThermoAnalytics, Inc), which implements the Fiala [3,4] thermoregulation model.

Test protocol was adapted from previously performed human trials, where subjects dressed in full firefighter turnout gear performed a series of controlled treadmill work and rest cycles[6]. VO2max data was unavailable, so the work rate was calculated using the ASCM Walking Equation [5]for the two different activity periods and adjusted to account for the additional weight of the SCBA equipment. The metabolic rate for the rest periods was estimated based on the prior activity period work rate to account for some level of sustained metabolic heat generation following exercise.

The turnout ensemble, Figure 1, consisted of outer shell (7,5 oz para-aramid/PBI fabric), moisture barrier (5.3 oz e-PTFE laminated to meta-aramid fabric), and thermal liner (para-aramid needle-punched fabric quilted to meta-aramid fabric). Under garments included underwear, shorts, t-shirt, socks. Accessories included firefighter boots, gloves, flash fire hood, helmet, SCBA and mask.

Figure 1 – Garment Ensemble Under Test

The manikin was seated in a wheelchair outside the chamber and preheated to thermoneutral conditions (Tsk=34.1 °C) prior to the test. The physiological model was also initialized to thermoneutral state (Thy=37.24 °C), defining tissue layer and blood pool temperatures for each limb. Once manikin and chamber had achieved stable conditions, the test sequence, Table 1, was carried out.

Table 1 – Test Protocol

Test Period	Time (min)	Work Rate (MET)	Simulated Activity Description
1	15	1	Rest- seated outside environmental chamber
2	10	1	Enter environmental chamber set to 31.1 deg C, 50% RH. Rest- seated
3	20	4.07	Walk on level grade treadmill @ 2.7 mph
4	15	2	Rest- seated inside environmental chamber with mask off and coat open
5	20	6.17	Walk on 5% grade treadmill @ 2.7 mph
6	10	3	Rest- seated with mask and coat in place
7	20	2	Exit environmental chamber. Rest- seated outside chamber.

RESULTS

The adaptive manikin system is currently designed to represent the 50th percentile male morphology and physiology. The existing human subject data included a wide range of subject weights (72.2-101.5 kg). Analyses were performed to relate the adaptive manikin skin and core temperature response to the both the full subject population (85 +/-10 kg, n=7) and a weight representative subset (73 +/- 1 kg, n=2) best representing the 50th percentile target. Variance between human results and replicate manikin studies was also analysed.

Figure 2 shows agreement between the adaptive manikin system T_{hy} and the mean T_{re} for the two selected population groups. The similarity of the curves demonstrates that the manikin and regulation model are functioning properly. The rate of change of core temperature is generally faster for the manikin system than the human data, indicating a possible discrepancy with metabolic heat generation or the thermal mass represented in the physiological model. Additionally, the manikin was operated without active air flow from the SCBA system while test subjects had been supplied with cool dry air through the SCBA apparatus resulting in additional core heat loss.

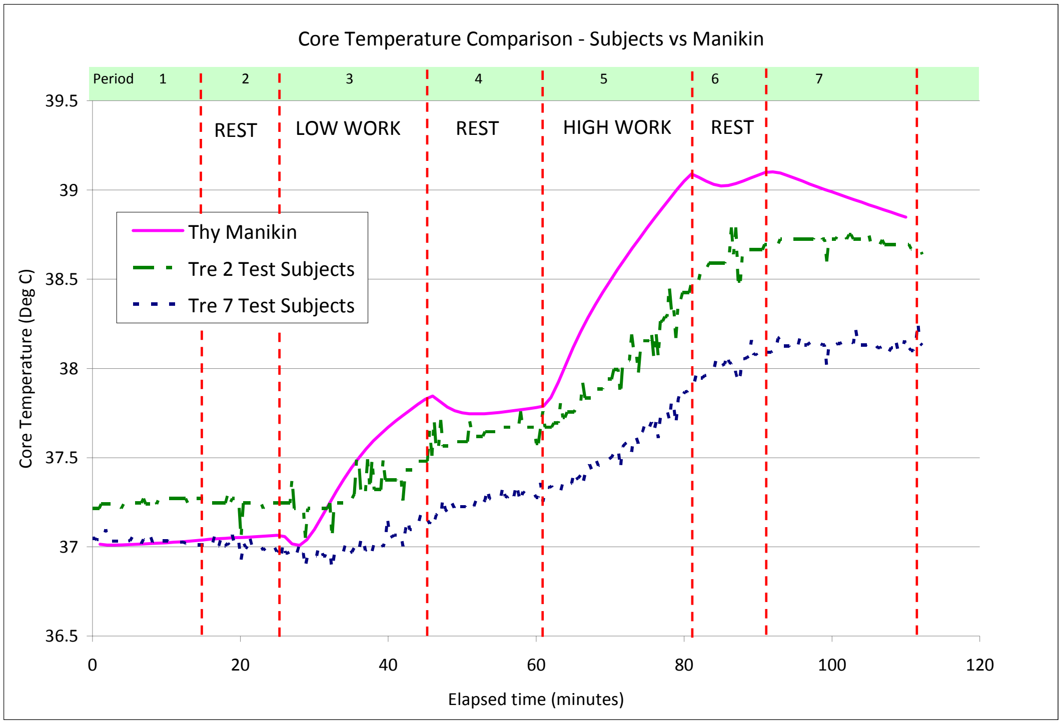

Figure 2 – Comparison of Subject Core Temperature with Adaptive Manikin

Figure 3 illustrates the agreement of skin temperature between the manikin and the human subjects. The characteristics and magnitude of the response curves indicate very good correlation with subject trials. The greatest discrepancies were found in the thighs and the face, which were both elevated above the test subject skin temperatures. It is believed that the thighs may have been influenced by the elevated core temperature during the high work period. The face temperature is likely due to testing the manikin with no SCBA airflow which was different from the subject protocol.

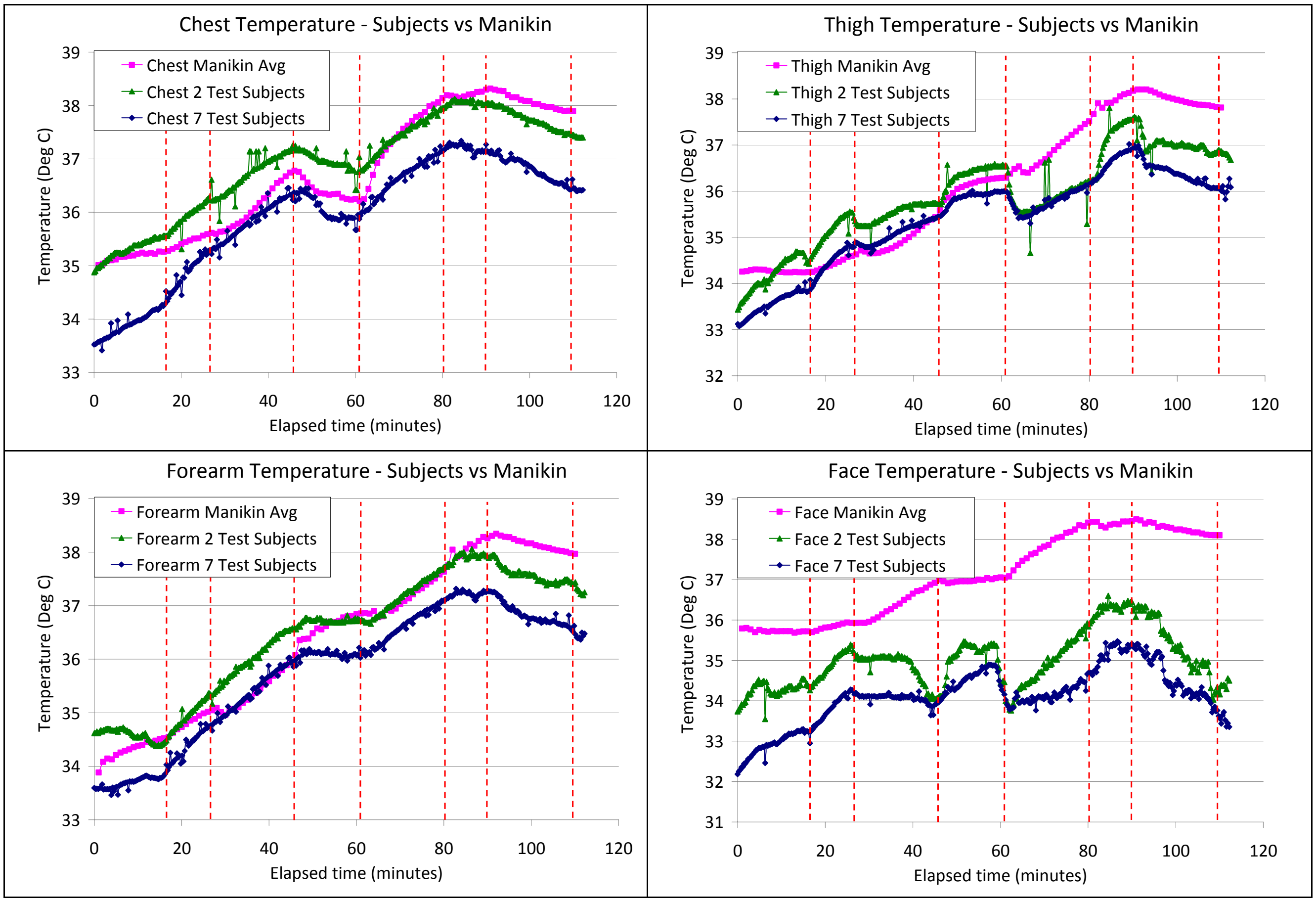

Figure 3 – Comparison of Subject Skin Temperature with Adaptive Manikin

A variance analysis, Table 2, was performed for both human subjects and the adaptive manikin system. In all cases, the variance increased over the duration of the trials. The variance of the manikin trials was significantly lower than that of the human subject study, confirming the repeatability of the adaptive manikin system

Table 2 – Mean Temperature (°C) and Standard Deviation at Time 0-15 Minutes

	Tcore	**Tchest**	**Tthigh**	**Tforearm**	**Tface**
Adaptive Manikin (n=3)	37.02 ±0.02	35.16 ± 0.12	34.26 ± 0.20	34.28 ± 0.17	35.73 ± 0.04
Full Subject Set (n=7)	37.03 ± 0.25	33.87 ±1.32	33.53 ±0.77	33.68 ±0.90	32.87 ±1.56
Weight-matched subjects (n=2)	37.25 ± 0.22	35.27 ± 1.04	34.17 ±0.37	34.60 ± 0.41	34.24 ±0.96

Table 3 – Mean Temperature and Standard Deviation at Time 80-90 Minutes

	Tcore	**Chest**	**Thigh**	**Forearm**	**Face**
Adaptive Manikin (n=3)	39.05 ± 0.15	38.20 ±0.16	37.92±0.24	38.03 ±0.24	38.40 ±0.16
Full Subject Set (n=7)	37.99 ±-0.46	37.20 ±0.62	36.60 ±0.59	37.21 ±0.51	35.14 ±1.09
Weight-matched subjects (n=2)	38.58 ± 0.22	38.05 ±0.16	37.10 ± 0.90	37.90 ±0.06	36.28 ±0.26

CONCLUSIONS

Two key conclusions were established from this preliminary study. First, good agreement was achieved between manikin and human subject core temperatures despite some uncertainty regarding actual work rates during the human trials. Core temperature increased in the manikin at a slightly higher rate than in the comparable human subjects which is theorized to be based on a slight metabolic rate or thermal mass discrepancy in the physiological model. Agreement of skin temperature was excellent, with some variation in the face and upper arms largely attributable to the mask and garment handling procedure. Second, the test-to-test repeatability was demonstrated to be excellent. Same-operator variability was indiscernible, and operator-specific test execution resulted in a slight response variation over time. The results from the manikin + model closely mimicked the human subjects and the repeatability exceeded that of the human subject results.

Future work is recommended to improve and further validate the adaptive manikin system. A physiological study including continuous measurement of VO2 needs to be performed incorporating a wider range of Personal Protective Equipment (PPE). In addition, the thermal manikin should be fitted with the capability to measure the temperature and humidity of breathing air to provide a more accurate assessment of the heat loss provided by reseparation.

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