FURTHER VALIDATION OF THE MODEL-CONTROLLED NEWTON THERMAL MANIKIN AGAINST HISTORICAL HUMAN STUDIES

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INTRODUCTION

This work is a continuation of a project started in 2009[1] to validate a new integrated physiological simulation tool based on the "Newton" thermal manikin from Measurement Technology Northwest and a physiological/comfort model "Manikin PC^2" based on the RadTherm finite difference thermal analysis program from ThermoAnalytics, Inc. The computation algorithms in Manikin PC^2 are based on the physiological regulation model of Fiala[2,3], and comfort model from UC Berkeley[4]. Previous work was focused on ensuring convergence and stability of the manikin plus regulatory model, and agreement of the combined tool against simulation-only results. This extension to the prior study has focused on completing a set of experiments intended to replicate historical and established human subject studies in both steady state and transient environmental conditions.

METHODS

The 26 zone thermal manikin "Newton", Figure 1, 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. The integrated system recomputes setpoints and adjusts heating power every 9 seconds.

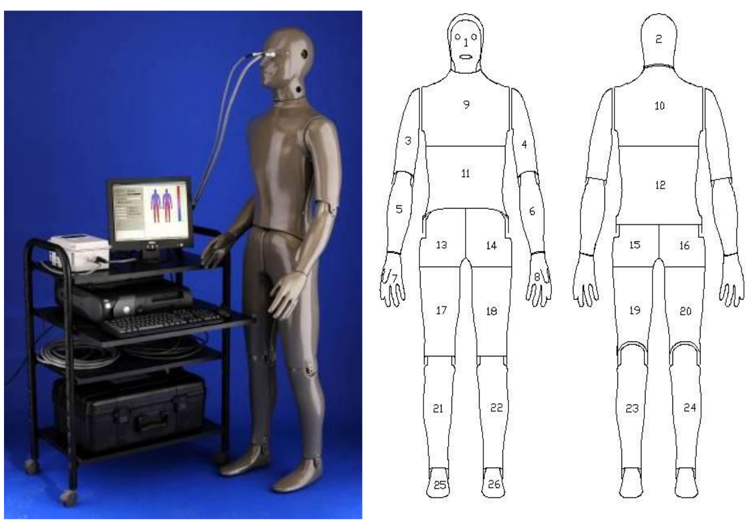

Figure 1 – Newton Thermal Manikin

The manikin + model was evaluated for convergence at a thermoneutral state (T_a=30°C, Rh=40% , v_a <= 0.45 m/s, M=0.8). In this thermoneutral state, a snapshot of the surface temperatures, tissue temperatures, and blood pool temperatures was stored. Saving these thermoneutral setpoints allowed subsequent experiments to begin from precisely the same physiological condition.

Three sets of experiments were performed to replicate past human studies published by Stolwijk/Hardy (SH) [5], Werner/Reents (WR) [6], and Raven/Horvath (RH) [7]. Test protocols for each experiment set are listed below in Table 1, 2, & 3.

Table 1 WR Test Conditions

Experiment Type: Fixed Temperature, Steady State		**Garment:** Sweating Skin
Description: Manikin was placed on a cot in an environmental chamber at the desired ambient conditions and skin temperatures were set to thermoneutral setpoints. After skin temperatures were steady, model control was started and allowed to run for the specified duration.		
Test Name	**Ambient Conditions**	**Test Duration**
WR Run 1	T_a = 30 °C, Rh = 40%*[1], v_a <= 0.45 m/s	120 min
WR Run 2	T_a = 20 °C, Rh = 40%*[1], v_a <= 0.45 m/s	120 min
WR Run 3	T_a = 10 °C, Rh = 40%*[1], v_a <= 0.45 m/s	90 min

Table 2 SH Test Conditions

Experiment Type: Transient – hot step change		**Garment:** Sweating Skin
Description: The manikin skin temperatures were set to thermoneutral setpoints. After skin temperatures were steady, model control was started and the manikin was seated in a wheel chair in 28 °C ambient conditions for 1 hour. Next, the manikin was transferred to a chamber at the desired ambient conditions for 2 hours and then returned to the 28 °C chamber for 1 hour.		
Test Name	**Ambient Conditions**	**Test Duration**
SH Run 1	T_a = 37.5 °C, Rh = 40%*[1], v_a <= 0.3 m/s	60-120-60 min
SH Run 2	T_a = 42.5 °C, Rh = 40%*[1], v_a <= 0.3 m/s	60-120-60 min
SH Run 3	T_a = 47.5 °C, Rh = 40%*[1], v_a <= 0.3 m/s	60-120-60 min

Table 3 RH Test Conditions

Experiment Type: Transient – cold step change		**Garment:** Sweating Skin
Description: The manikin skin temperatures were set to thermoneutral setpoints. After skin temperatures were steady, model control was started and the manikin was placed in a wheel chair inside an environmental chamber at 28 °C ambient conditions for 1 hour. Next, the manikin was placed in a chamber at the desired ambient conditions for 2 hours.		
Test Name	**Ambient Conditions**	**Test Duration**
RH Run 1	T_a = 5 °C, RH = 40%*[1], v_a <= 0.3 m/s	60-120 min

*[1]Rh of 40% was used by model software to calculate accurate basal sweat rates and respiration heat losses, actual Rh was 30% ± 10%, except for RH Run 1 which had an Rh of 65% ± 10%.

RESULTS

The skin temperature distributions for the manikin and WR human data, Figure 2, were in close agreement at a 30 °C ambient. As the ambient temperatures got colder, the individual zone temperature distribution became less accurate; however, the overall mean skin temperature of the manikin trended very well with the human data. These differences in skin temperature distribution may be attributed to how are model distributes skin temperatures when compared to the six subjects used by WR, but it is inconclusive.

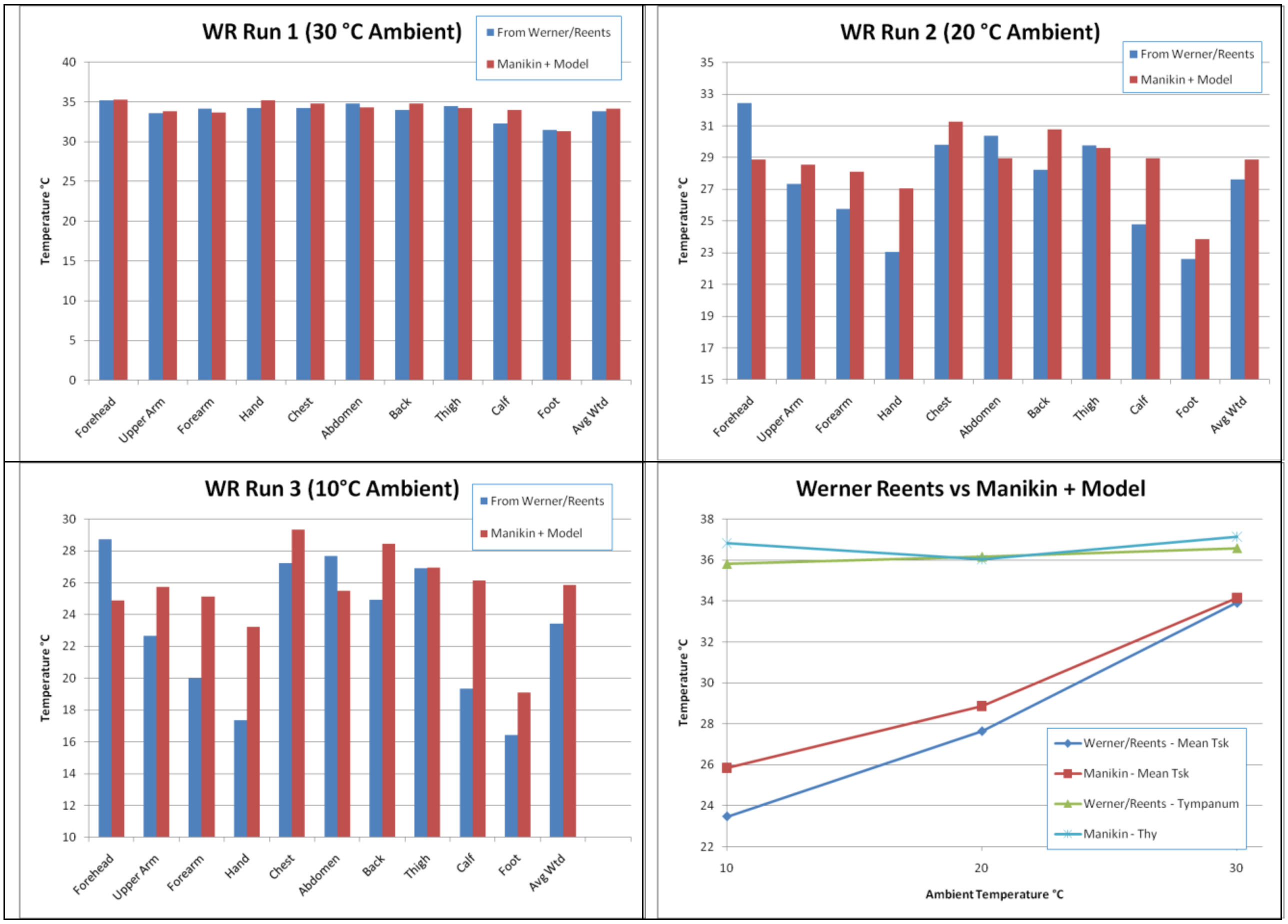

Figure 2 WR Run Agreements with Werner/Reents Human Data

The manikin core temperature was higher than the WR reported tympanic temperature at T_a=10°C and T_a=30 °C ambient, but the T_a=20 °C condition matches closely. These differences in core temperature could be attributed to fact that the manikin protocol may have included a different transient profile than the WR test method, which did not explicitly describe the transient processes. Raven & Horvath (1970) discuss that the intensity of the metabolic response can differ greatly at different ambient temperatures; specifically, “Williams and Loots (1968) have also shown that rectal temperatures were greater at the end of exposure at 5 °C than at 10 °C”. This could help to explain the higher core temperature we observed at 10 °C.

Figure 3 shows the response characteristics from the SH experiments. The three curves represent the human data, the measured Tsk of the manikin + model, and the results from a full simulation using the RadTherm interface to the ManikinPC^2 regulation model. The agreement with human data was good for the transient exposure to 37.5 °C and 42.5 °C environments.

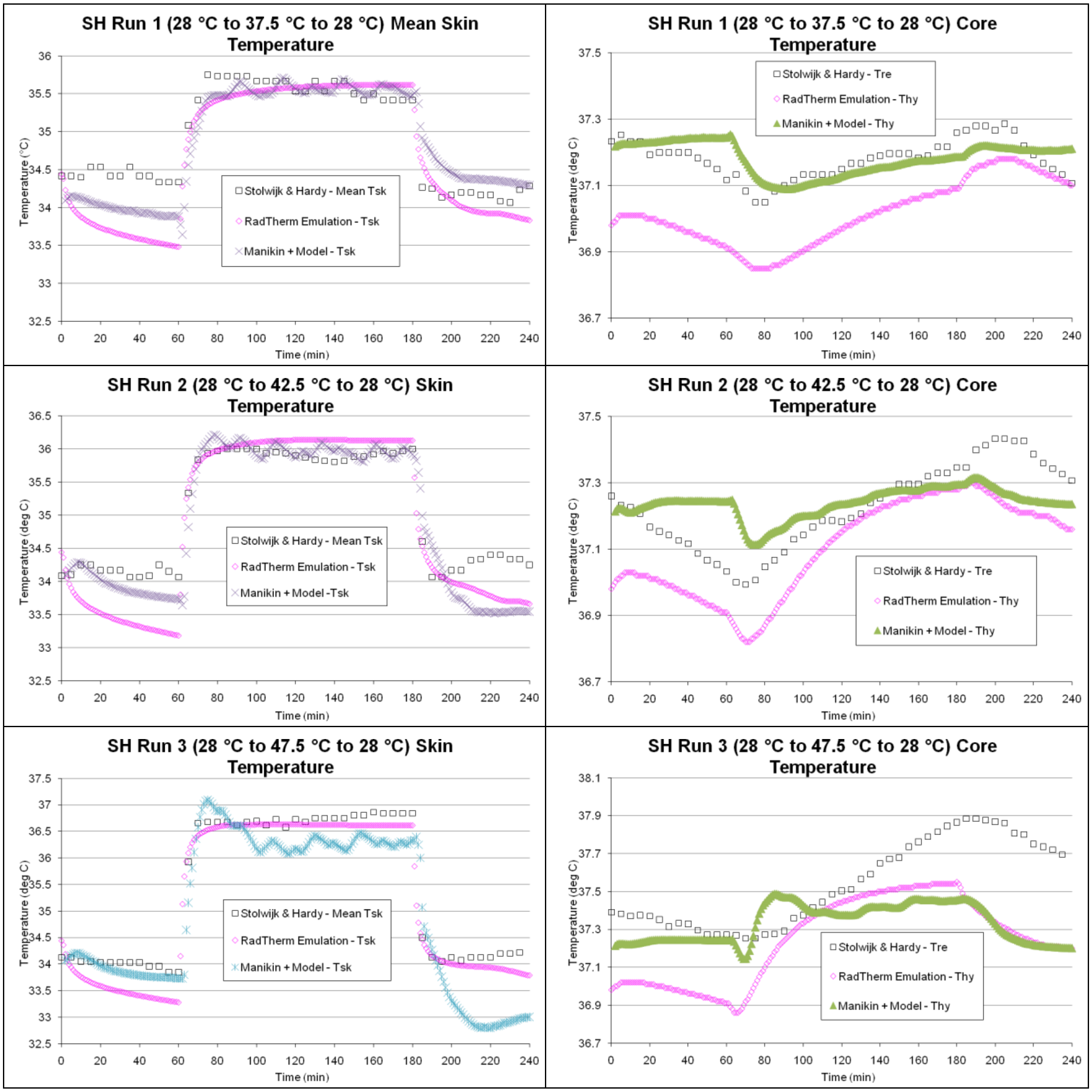

Figure 3 SH Run Agreement with Stolwijk/Hardy Human Data

At T_a=47.5 °C the manikin skin temperature overshoots the human subject data on both increasing and decreasing ambient temperature. The manikin skin temperature response varied the greatest from the RadTherm Emulation response curve in these conditions, indicating the manikin is not tracking the model setpoints adequately. It is believed that both of these effects are due to the manikin operating at the upper limit of ambient temperature. On transition to the hot room, the manikin skin temperature overheated, resulting in delivery of excess sweating volume to the surface. This surplus sweat volume overcooled the skin and core temperatures, and contributed to Tsk undershoot during the hot-to-neutral environment transition.

Figure 4 shows the agreement of the mean Tsk for the manikin and RH human data was excellent for the 28 °C to 5 °C transient. However, the core temperature for manikin and RH human data did not correlate very well over the duration of the test. The manikin response is consistent with the how the manikin + model responded to the previous WR cold tests. The subjects of RH appear to have a higher level of initial vasoconstriction than the manikin + model, causing their core temp to rise following cold exposure.

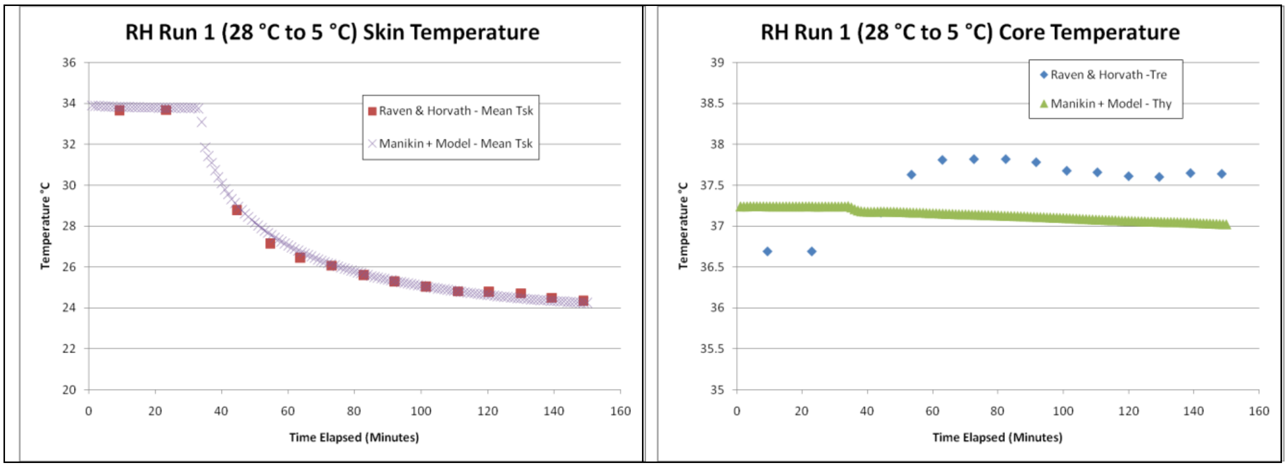

Figure 4 RH Run Agreement with Raven/Horvath Human Data

CONCLUSIONS

The agreement between manikin/model and historical data sets ranged from good to excellent, with the best agreement on mean skin temperature for all test environments. Core temperature and regional skin temperature distribution correlated best at moderate temperatures and diverged from the historical human subject data as the temperatures approached hot or cold extremes. These results indicate that the Newton thermal manikin regulated by Manikin PC^2 software can be a useful tool to emulate human physiological response over a range of ambient conditions. Additional study is recommended to more accurately characterize response of this system at extreme high and low ambient temperatures.

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