8I3MMM

Eighth International Meeting for Manikins and Modeling

Victoria, BC, Canada
August 22-26, 2010

Spin Sport Innovation Centre
Pacific Institute for Sport Excellence
MEASUREMENT Technology NORTHWEST

Conference Program and Abstracts

8I3MMM

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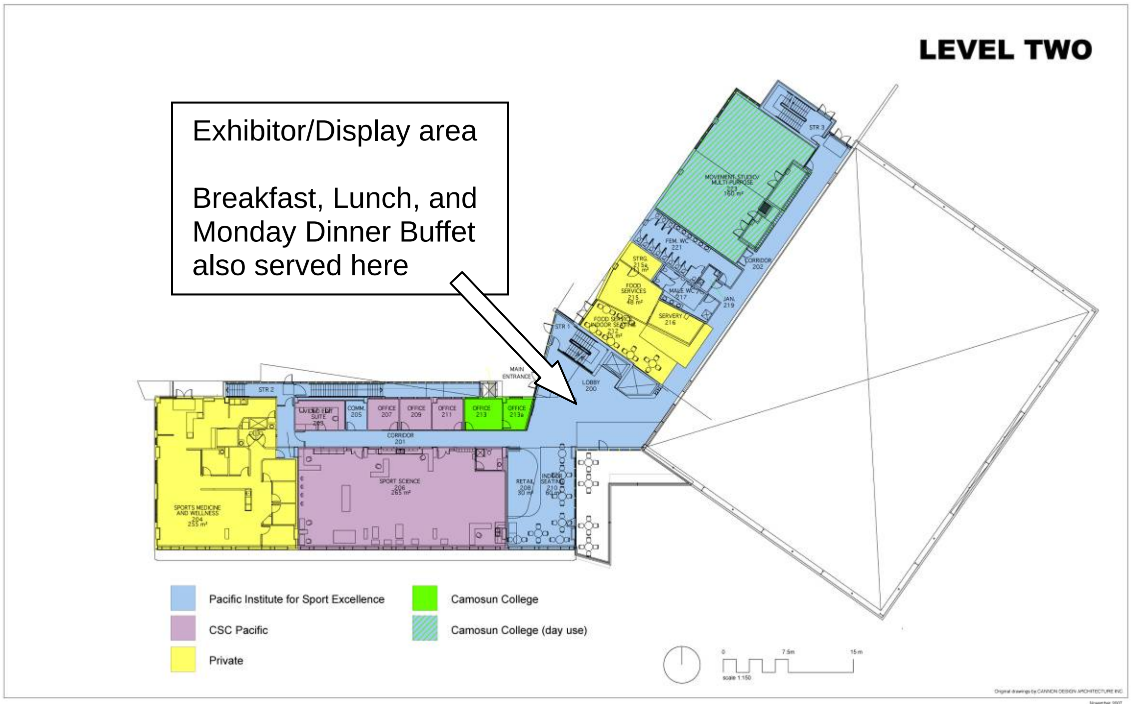
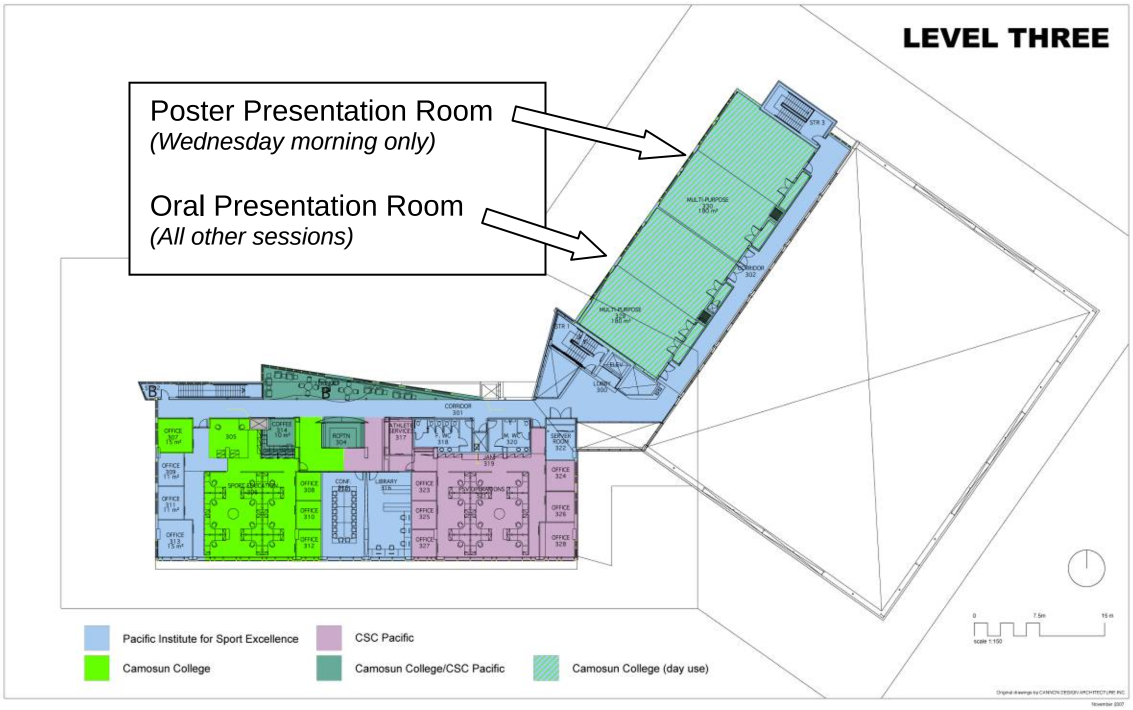

Exhibitor/Display area

Breakfast, Lunch, and Monday Dinner Buffet also served here


Poster Presentation Room
(Wednesday morning only)

Oral Presentation Room
(All other sessions)

8I3M – SOCIAL PROGRAM

Sunday, August 22, 2010 - Hotel Grand Pacific

6:00 PM	CONFERENCE REGISTRATION AND WELCOME RECEPTION *- Vancouver Island Ballroom. Hot and Cold Food Selections, Beverage Selections*

Monday, August 23, 2010 - Pacific Institute of Sport Excellence

5:00 PM	MONDAY DINNER BUFFET *- 2nd Floor Foyer and Deck. Four Hot Entrees, Salad, Side, and Beverage Selections*

Thursday, August 26, 2010 - Hotel Grand Pacific

7:00 PM	FAREWELL DINNER BANQUET *- Vancouver Island Ballroom. Choice of Four Entrees, Wine and Beverage Selections*

8I3M - SCIENTIFIC PROGRAM OVERVIEW

MONDAY

Session 1: HUMAN MODELS AND HUMAN STUDIES
Session 2: STANDARDS

TUESDAY

Session 3: MANIKIN DEVELOPMENTS.1
Session 4: MANIKIN DEVELOPMENTS.2
Session 5: FLAME EXPOSURE MANIKINS
Session 6: MODEL-CONTROLLED MANIKINS

WEDNESDAY

Session 7: MANIKIN METHODOLOGY
Session 8: POSTER PRESENTATIONS

THURSDAY

Session 9: ADVANCED CLOTHING SYSTEMS.1
Session 10: ADVANCED CLOTHING SYSTEMS.2
Session 11: CLOTHING MODELS

*Session groupings are approximate and are subject to change.

8I3M - SCIENTIFIC PROGRAM

Monday, August 23, 2010 - Pacific Institute for Sport Excellence

9:00 AM	**BREAKFAST, 2nd Floor Foyer** **(Registration Desk Open)**
10:00 AM	Welcome and Opening Remarks – 3rd Floor Classrooms
10:30 AM	SWEAT DISTRIBUTION DURING REST IN THE YOUNG CHILDREN *Kazuyo Tsuzuki*
10:50 AM	ASSESSMENT OF THERMAL CLIMATE AND HUMAN COMFORT WHEN USING ALTERNATIVE HEATING METHODS IN CHURCHES *H.O. Nilsson and T. Broström*
11:10 AM	PREDICTION OF THERMAL COMFORT IN NON-HOMOGENOUS ENVIRONMENT BY MEANS OF MULTI-SEGMENTED MODELS *J. Pokorny, J. Fiser, M. Jicha*
11:30 AM	PHYSIOLOGICAL CHALLENGES FOR HUMANS WEARING SURVIVAL SUITS DURING COLD WATER IMMERSION *Matthew White*
12 NOON	**LUNCH BUFFET, 2nd Floor Foyer**
1:30 PM	SPIN/PISE Host Facility Tour
3:00 PM	DOES PHS (PREDICTED HEAT STRAIN) MODEL PREDICT ACCEPTABLE SKIN AND CORE TEMPERATURES WHILE WEARING PROTECTIVE CLOTHING? *Faming Wang, Chuansi Gao, Kalev Kuklane, Ingvar Holmér*
3:20 PM	WBGT HEAT BALANCE EQUATION INCLUDING GRAY GLOBE TEMPERATURE – CORRECTION OF WBGT FOR SOLAR RADIATION ABSORPTION *Tomonori Sakoi, Tohru Mochida, Kohei Kuwabara*
3:40 PM	EUROPEAN MANIKIN STANDARDS AND MODELS TO CALCULATE THERMAL INSULATION *Kalev Kuklane, Chuansi Gao, Faming Wang, Ingvar Holmér*
4:00 PM	Social/Networking Session
5:00 PM	**DINNER BUFFET – 2nd Floor Foyer and Patio**
7:00 PM	Shuttle bus returns to Hotel Grand Pacific

8I3M - SCIENTIFIC PROGRAM

Tuesday, August 24, 2010 - Pacific Institute for Sport Excellence

8:00 AM	**BREAKFAST, 2nd Floor Foyer**
9:00 AM	COMMISIONING OF A WATER CALORIMETER FOR USE IN THE CALIBRATION OF SUBMERSIBLE THERMAL MANIKINS *A. Kuczora, P. Hackett, M.B. DuCharme, B. Farnworth, L. Mak*
9:20 AM	CALIBRATION OF A SUBMERSIBLE THERMAL MANIKIN USING A WATER CALORIMETER *M.B. DuCharme, A. Kuczora, B. Farnworth, L. Mak*
9:40 AM	DEVELOPMENT OF EMPIRICAL EQUATIONS TO PREDICT SWEATING SKIN SURFACE TEMPERATURE FOR THERMAL MANIKINS IN WARM ENVIRONMENTS *Faming Wang, Kalev Kuklane, Chuansi Gao, and Ingvar Holmér*
10:00 AM	COMPARISON OF EVAPORATIVE RESISTANCE USING THE THERMISTOR ON THE WET SKIN AND THE SHELL IMBEDDED WIRE TEMPERATURE SENSOR *Satoru Ueno, Shin-ichi Sawada*
10:20 AM	**BREAK (Coffee/Tea & Assorted Beverages)**
10:40 AM	MEASUREMENT OF MOISTURE TRANSPORT AND ACCUMULATION PROCESSES INSIDE 3-DIMENSIONAL CAR SEAT AND UPHOLSTERY CONSTRUCTIONS WITH A SITTING SWEATING MANIKIN *Gesine Schrammel, Boris Bauer*
11:00 AM	DEVELOPMENT OF A MANIKIN SKIN SIMULANT FOR USE IN THE MAN-IN-SIMULANT-TEST *R. Bryan Ormond, Roger L. Barker, Donald B. Thompson, Keith R. Beck, Gerardo A. Montero*
11:20 AM	DEVELOPMENT OF A ROBOTIC THERMAL MANNEQUIN FOR EVALUATION OF INDIVIDUAL PROTECTIVE ENSEMBLES *Richard Burke, Steve Rodriguez, Nathan Lanci*
11:40 AM	DEVELOPMENT OF A THERMAL CHILD MANIKIN *Martin Harnisch, S. Anja Mueller, Jan Beringer*
12 NOON	**LUNCH BUFFET, 2nd Floor Foyer**
1:30 PM	MANNEQUIN FLAME EXPOSURE TESTS FOR EVALUATING PROTECTIVE CLOTHING *J.D. Dale, S. Paskaluk, M.Y. Ackerman, E.M. Crown*

1:50 PM PYROHANDS: MANIKIN HANDS FOR MEASURING THE THERMAL PROTECTIVE PERFORMANCE OF GLOVES IN FLASH FIRES
Alexander C. Hummel, Roger L. Barker, Kevin M. Lyons, A. Shawn Deaton, John Morton-Aslanis

2:10 PM A NUMERICAL MODEL FOR INTRUMENTED MANNEQUIN FLASH FIRE EVALUATION SYSTEM – A PARAMETER STUDY TO IMPROVE GARMENT PROTECTIVE PERFORMANCE
Guowen Song

2:30 PM OPPORTUNITIES AND CONSTRAINTS OF PRESENTLY USED THERMAL MANIKINS WHEN USED FOR SIMULATION OF THE HUMAN BODY
A. Psikuta, R. Rossi

2:50 PM BREAK (Coffee/Tea & Assorted Beverages)

3:10 PM IMPLEMENTATION OF THERMO-PHYSIOLOGICAL CONTROL ON A MULTI-ZONE MANIKIN
Bernard Redortier, Thomas Voelcker

3:30 PM THERMOREGULATORY MANIKINS ARE DESIRABLE FOR EVALUATIONS OF INTELLIGENT CLOTHING AND SMART TEXTILES
Chuansi Gao, Kalev Kuklane, Ingvar Holmér

3:50 PM APPLICATION OF MODEL-CONTROLLED MANIKIN TO PREDICT HUMAN PHYSIOLOGICAL RESPONSE IN FIREFIGHTER TURNOUT GEAR
Richard Burke, Keith Blood, A. Shawn Deaton

4:15 PM Adjourn for the day

4:30 PM Shuttle bus returns to Hotel Grand Pacific.
No other 8I3M activities are scheduled for the day.
Enjoy free time to see Victoria-area attractions.

8I3M - SCIENTIFIC PROGRAM

Wednesday, August 25, 2010 - Pacific Institute for Sport Excellence

8:00 AM BREAKFAST, 2nd Floor Foyer

9:00 AM A COMPARISON OF HEAT LOSS MEASUREMENTS ON MANIKINS AND HUMANS WEARING DRY IMMERSION SUITS
M.B. DuCharme, B. Farnworth, P. Hackett, A. Kuczora, L. Mak, P. Potter, D. Sweeney, W. Uglene

9:20 AM EVAPORATIVE RESISTANCE AND THERMAL INSULATION OF CLOTHING UNDER DIFFERENT POSTURE POSITIONS
Y.S. Wu, J.T. Fan, and W. Yu

9:40 AM A PRACTICAL METHOD FOR DETERMINING CONTACT AREA DIFFERENCES BETWEEN HUMANS AND THERMAL MANIKINS SITTING IN INFLATABLE LIFERAFTS
Robert Brown, Stephen Penney, Scott N. MacKinnon, Fabien A. Basset, Lawrence Mak, Andrew Kuczora, Michel B. DuCharme, Stephen S. Cheung, Brian Farnworth

10:00 AM EVALUATION OF VENTILATION AND THERMAL PROTECTION REQUIREMENTS IN LIFEBOATS WITH A THERMAL MANIKIN AND MATHMATICAL MODEL
Lawrence Mak, Andrew Kuczora, Brian Farnworth, Robert Brown, Michel B. DuCharme

10:20 AM BREAK (Coffee/Tea & Assorted Beverages)

10:40 AM POSTER SESSION – INTRODUCTORY COMMENTS FROM AUTHORS

COST-EFFECTIVE AND EASY-TO-USE SWEATING FOOT MODEL, DEVELOPMENT AND FIRST RESULTS
Carsten Zimmermann, Wolfgang Uedelhoven, Bernhard Kurz, Martin Rottenfusser

COMPARISON OF MICROCLIMATE BETWEEN A BREATHABLE AND A NON-BREATHABLE SHOE
Martin Harnisch, Frank I. Michel, Kerstin Witte, Thi Van Anh Nguyen, Robert Leimer

EFFECT OF LOAD, ITS DISTRIBUTION ON CLOTHING SYSTEM THERMAL PROPERTIES, AND PREDICTED HUMAN THERMAL RESPONSES
J.A. Gonzalez, L.G. Berglund, and M. Yokota

EXPERIMENTAL STUDY OF NON-UNIFORM THERMAL ENVIRONMENT AROUND HUMAN BODY USING A THERMAL MANIKIN
Ikue Mori, Kazuyo Tsuzuki, Tomonori Sakoi, and Takuya Kataoka
A PORTABLE CALORIMETER FOR THE CALIBRATION OF THERMAL MANIKINS
Renee Boileau, Brian Farnworth, Michel B. DuCharme, Lawrence Mak

THERMAL MANIKIN EVALUATION OF ENSEMBLE DESIGNS INTENDED TO REDUCE THERMAL BURDEN
Thomas Endrusick, Laurie Blanchard, Marc Mathews, Jason Saylor, Andra Kersteins and Stephanie Tew

HUMAN ADAPTATION TO HEAT DURING EXERCISE
I. Yermakova, A. Bortkiewicz, E. Gadzicka, N. Nikolaienko

COMPARATIVE STUDY OF VARIOUS UNDERGARMENTS UNDER A DRY SUIT USING AN IMMERSIBLE THERMAL MANIKIN
Pratibha Sinha, Marshall Lew Nuckols

FURTHER VALIDATION OF THE MODEL-CONTROLLED NEWTON THERMAL MANIKIN AGAINST HISTORICAL HUMAN STUDIES
Keith Blood, Richard Burke

THERMAL AND EVAPORATIVE HAND MANIKIN WITH GRIPPING MECHANISM
Ales Jurca, Mitja Babic

12 NOON **LUNCH BUFFET, 2nd Floor Foyer**

1:30 PM Adjourn for the day

1:45 PM Shuttle bus returns to Hotel Grand Pacific.
No other 8I3M activities are scheduled for the day.
Enjoy free time to see Victoria-area attractions.

8I3M - SCIENTIFIC PROGRAM
Thursday, August 26, 2010 - Pacific Institute for Sport Excellence

8:00 AM	**BREAKFAST, 2nd Floor Foyer**
9:00 AM	THERMAL MANIKIN EVALUATION OF PROTOTYPE ARM AND SHOULDER ARMOR *Donna H. Branson, Panagiotis Kamenidis, Semra Peksoz, Huiju Park, Su Kyoung An, Cathy Starr*
9:20 AM	COOLING CAPACITY DETERMINATION FOR BODY VENTILATION SYSTEMS *Xiaojiang Xu and Julio Gonzalez*
9:40 AM	BIOPHYSICS OF BODY ARMOR ENSEMBLES AND THE IMPACT ON PREDICTED HUMAN THERMAL RESPONSES *Miyo Yokota, Julio A. Gonzalez, Larry G. Berglund*
10:00 AM	COMPARISON OF THERMAL AND EVAPORATIVE RESISTANCE BETWEEN TWO GARMENT DESIGNS DRIVEN BY MATERIAL CHARACTERISTICS USING A THERMAL MANIKIN *J. Brady, T. Rioux, N. Rao, and C. Winterhalter*
10:20 AM	**BREAK (Coffee/Tea & Assorted Beverages)**
10:40 AM	FUNCTIONAL APPAREL DESIGN FOR THE HUMAN TORSO *Patrick Kinnicutt, Tanya Domina, Maureen Macgillivray, Thamizhisai Periyaswamy, Terry Lerch*
11:00 AM	CHALLENGES OF HUMAN THERMAL MODELING *Eugene H. Wissler*
11:20 AM	CORE TEMPERATURE PREDICTION MODELING USING A SWEATING MANIKIN *Semra Peksoz, Huantian Cao, Huiju Park, Su Kyoung An, Donna Branson*
11:40 PM	A STUDY ON THE EFFECT OF AIR GAP ON COMFORT PROPERTIES FOR FABRIC SYSTEMS USED IN PROTECTIVE CLOTHING *Guowen Song, Tian Tang, André McDonald, Lidan Song, and Dan Ding*
12 NOON	**LUNCH BUFFET, 2nd Floor Foyer**
1:30 PM	CHARACTERIZATION OF THE THERMAL AND EVAPORATIVE RESISTANCE OF CLOTHING FOR USE IN SEGMENTAL MODELS OF HUMAN THERMOREGULATION *Mark Hepokoski, Allen Curran*
1:50 PM	MOISTURE AND CLOTHING LAYERS: EFFECT OF AMBIENT TEMPERATURE ON HEAT LOSS AND INSULATION *Kalev Kuklane, Otto Henriksson, J. Peter Lundgren, Ingvar Holmér*

2:10 PM	Closing Remarks
2:30 PM	Shuttle bus returns to Hotel Grand Pacific. Enjoy free time prior to the 8I3M’s Farewell Banquet (7PM).

SWEAT DISTRIBUTION DURING REST IN THE YOUNG CHILDREN

Kazuyo Tsuzuki

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In order to investigate the relationship between sweat gland density and its distribution over the body, sweat rates on the local skin area in naked children were investigated using the evaporimeter in the climatic chamber.

The evaporimeter was utilized to measure transepidermal water loss from the skin surface. The child subjects were six boys and four girls ranging in age from 1-5 years. They were sitting on the chair and separately exposed to four environmental conditions; air temperature of 28 °C, 31 °C, 34 °C, and 37 °C with 35% relative humidity. The local sweat rates at fourteen skin areas were measured by the experimenter. Rectal and skin temperatures were continuously measured by the thermister thermometer. Before and after the measurement period the body mass was measured by the platform scale and body mass loss was calculated from the difference.
The relationship between the local sweat rate and the sweat gland density which was provided elsewhere (Ogata K., J Orient. Med. 23:1155-1186, 1935) was investigated to confirm the regional difference over the body. The good correlationship between the local sweat rate and sweat gland density were found significantly at 28 °C for both children and young women groups (r= 0.67, 0.9, respectively), 34 °C and 37 °C for the young women group (r= 0.71, 0.65, respectively). The higher sweat gland density shows the higher sweat rate at the local identical body area.

The local sweat rates in the young children were compared with those in the young women, which was already provided elsewhere (Chung M-H, Tamura T., J.Hum and Living Envir 5(2): 123-131, 1998). There was no significant difference in the local sweat rate on the forehead and proximal parts between the children and the young women at 28 °C and 34 °C. The sweat rates on the upper and lower limbs were significantly higher in the children than the young women at 28 °C and 34 °C. The sweat rates on the chest, lower back, upperarm, forearm, back of hand, shin, and foot were significantly higher in the children than the young women at 37 °C. The sweat rates on the thigh and calf were significantly lower in the children than the young women at 37 °C.

These results can be used in clothing design, thermo-physiological modeling, and thermal simulation.

ASSESSMENT OF THERMAL CLIMATE AND HUMAN COMFORT WHEN USING ALTERNATIVE HEATING METHODS IN CHURCHES

H.O. Nilsson[1] *and T. Broström*[2]

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A first objective with this survey has been to map and evaluate the thermal comfort experience in a church with a radiant heating system. Since each degree has great importance for the energy use is the one objective to give a better answer on the question: Which settings and temperatures should be used during a ceremony?

The measurements have been carried out with a so-called comfort meter, an air speed transducer and a number of temperature- and air humidity loggers positioned in and around subjects. With these assessment method is it possible to consider the total effect of clothing, activity, air temperature, humidity, mean radiant temperature and air speeds on the human body. The measured predicted mean votes (PMV) have now been compared with actual mean votes (AMV) from over 100 churchgoers.

One other objective with the survey have been to produce information about which clothing church goers actually uses in order to correctly simulate and construct new energy efficient heating systems. An overall objective is to develop methods for dimensioning radiant heating systems used with low air temperatures. Important is to check the risk for draught, that in this case is dependant of the construction of the church benches. The time for pre-heating of the church, the radiator crowns height over the floor and the length of the ceremony are other factors that we now can begin to develop guidelines for.

With the results from this survey can we conclude considerably more about which climate that people in general, with different age, clothing and metabolism, can to intend to accept in it radiant heated church environment. With a mean clothing insulation of 1,3 clo would in this survey around 70% of church goers be pleased with the climate experience at only 12 degrees centigrade air temperature. More clothing and slightly higher temperatures can hence give even better results. An important factor that was forwarded through the comments in this survey is to compensate for the cold floor with correctly dimensioned floor heating, decreased draught and the use of warm shoes. We now have a much better basis in order to calculate what future systems should deliver, in the form of temperatures, distances, air speeds and also recommendations for better clothing to use.

PREDICTION OF THERMAL COMFORT IN NON-HOMOGENOUS ENVIRONMENT BY MEANS OF MULTI-SEGMENTED MODELS

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To correctly predict thermal comfort in non-homogenous environment, it is recommended to use multi-segmented physiological models in the combination with models for thermal comfort. In the paper, the authors refer on coupling of a physiological model by Tanabe with Zhang model for thermal comfort. As a result of the coupled model, distribution of surface temperatures for individual parts of human body (according to Tanabe model) and prediction of thermal comfort (according Zhang model) for these individual parts of human body is obtained.

Both models are designed for steady and dynamic conditions of ambient environment. The model is implemented in OpenModelica language using graphical environment SimForge.

PYSIOLOGICAL CHALLENGES FOR HUMANS WEARING SURVIVAL SUITS DURING COLD WATER IMMERSION

Matthew White

Simon Fraser University

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The purpose of this presentation is to give a both a summary of human physiological and cognitive responses to cold-water immersion as well as to illustrate how these responses influence human performance, safety and survival. The material will be given in the context of how survival suits help mitigate these responses and improve survivability.

With or without thermal protection garments, human performance and survival during cold-water immersion is largely dependent on maintaining peripheral as well as deep body core temperatures. In the seconds, minutes, to hours following cold-water immersion, there are a series of temperature-dependent physiological responses. These include the respiratory ‘gasp’ response, with either face-only or whole-body immersion, and this response dramatically increases the risk of drowning. Subsequently, during cold immersion there are dramatic decreases in upper limb function as evidenced by significant reductions in fine and gross motor skills. These performance decrements follow extensive cold-induced vasoconstriction and cooling of the skeletal muscle in the upper limb. The loss of upper limb performance with cooling is often referred to as a ‘physiological amputation’ and this prevents performance of simple lifesaving tasks. When protection of the body core temperature is inadequate, a metabolic shivering response prevails and from the early stages of hypothermia, cognitive decrements impair basic decision-making.

In conclusion, paramount in the employment of survival suits is protection of the body core and peripheral temperatures so as to reduce the physiological responses, improve upper limb function and maintain cognitive abilities.

Supported by Natural Sciences Engineering and Research Council of Canada.

DOES PHS (PREDICTED HEAT STRAIN) MODEL PREDICT ACCEPTABLE SKIN AND CORE TEMPERATURES WHILE WEARING PROTECTIVE CLOTHING?

Faming Wang, Chuansi Gao, Kalev Kuklane, and Ingvar Holmér

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Department of Design Sciences, Faculty of Engineering, Lund University, Sweden

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Mathematical modeling is very important when experimental settings with human subjects are restricted to thermal limits necessary to protect the individual. The predicted heat strain (PHS) model has been published AS ISO 7933 for about six years. It describes a method for predicting the sweat rate and internal core temperature that the human body will develop in response to the working conditions. The PHS model was developed based on thousands of laboratory and field experiments collected from eight European laboratories. However, most of the laboratory and field tests were performed on human subjects with light clothing ensembles (0.38±0.34 clo < Icl < 0.77±0.18 clo). The prediction of physiological responses while human wearing highly insulating protective clothing might be weak.

In order to check the prediction accuracy of current PHS model while using protective clothing, we conducted totally series of human subject tests at a simulated hot environment. The results of 18 tests involving the high visibility (HV), military (MIL) and firefighting (FIRE) clothing are reported here. Six human subjects were asked to walk on a treadmill at 4.5 km/h at 40 oC for 70 min. Two humidity levels were chosen: 2 kPa (RH = 27 %) and 3 kPa (RH = 41 %) depending on the garment. The rectal temperature, skin temperature, heart rate and metabolic rate were measured. The clothing and the subjects were weighed before and after the exposure in order to calculate the sweat and evaporation rate. The observed and predicted rectal temperatures and mean skin temperatures were compared. The PHS model failed to predict the final rectal temperature in FIRE and the predicted estimate was 1.83 oC higher than the observed value after 63-min exposure. The predicted curve showed a much deeper linear increase during the whole exercise. None of the predicted mean skin temperatures during the three testing scenarios were accurately predicted. The PHS model was consistently providing conservative mean skin temperature evaluations. The predicted curve in HV and MIL showed a much shallower increase during the early portion of the exposure and plateaued at temperatures lower than ever achieved by the subjects. The observed sweat rates were 556±110 g/h in HV, 717±200 g/h in MIL, and 834±274 g/h in FIRE. There was no significant difference between the predicted total sweat values and the experimental data (P=0.073).

In summary, the PHS model of core temperature has an unacceptable error when humans wore thick protective clothing. The weak prediction on the mean skin temperature in HV and MIL was in agreement with the empirical prediction equation in the source codes has the poorest and lowest correlation when a clothed human subject exercised at the humidity level above 2 kPa. It is therefore recommended that the PHS model should be amended to development and validated by manipulation of individual algorithms or physical (or physiological) parameters.

WBGT HEAT BALANCE EQUATION INCLUDING GRAY GLOBE TEMPERATURE – CORRECTION OF WBGT FOR SOLAR RADIATION ABSORPTION

Tomonori Sakoi [1]***, Tohru Mochida*** [2]***, Kohei Kuwabara*** [2]

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Wet Bulb Globe Temperature WBGT is thermal index for preventing heat disorder. It is expressed as the linear sum of wet bulb temperature T_w, black globe temperature T_{gB}, and air temperature T_a.

In the present study, we described the heat balance equation in terms of T_w, T_{gB}, T_a. Using this equation, we expressed skin temperature T_{sk} and heat storage rate to the human body S, as a linear equation of T_w, T_{gB}, and T_a and examined its characteristics. It was clarified that if there is an occurrence of solar radiation and if the solar absorption factor of the clothing used is low, T_{sk} might be overestimated by 7°C.

In order to evaluate the influence of the solar absorption factor of the clothing on the sensible heat transfer of the human body, we added gray glove temperature T_{gG} to the factors expressing heat stress, T_w, T_{gB}, and T_a. Then, we proposed the weighing ratio of a black globe temperature T_{gB}, θ and that of a gray globe temperature T_{gG}, $(1–\theta)$ from the heat transfer theory as shown in the following expressions.

$$\theta = \frac{-\varepsilon_G{}'' h_r + \varepsilon h_r{}''}{h_r\left(1-\varepsilon_G{}''\right)} \tag{1}$$

$$1-\theta = \frac{h_r - \varepsilon h_r{}''}{h_r\left(1-\varepsilon_G{}''\right)} \tag{2}$$

where, θ is coefficient for T_{gB}, $\varepsilon_G{}''$: solar absorptivity of gray globe thermometer, h_r: linear radiative heat transfer coefficient of human body with longwave radiation, ε: solar absorptivity of clothing surface, $h_r{}''$: linear radiative heat transfer coefficient of black and gray globe thermometers with longwave radiation, and $(1–\theta)$: coefficient for T_{gG}.

On the basis of these results, we derived a new WBGT heat balance formula that expressed T_{sk} and S, in terms of T_w, T_{gB}, T_{gG}, and T_a.

EUROPEAN MANIKIN STANDARDS AND MODELS TO CALCULATE THERMAL INSULATION

Kalev Kuklane, Chuansi Gao, Faming Wang, Ingvar Holmér

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ISO 9920 defines three insulation calculation methods: global, parallel and serial. It considers global method a general one that works in any situation, and parallel and serial could be used in specific cases. EN ISO 15831 is the basic manikin testing standard. It gives only two possibilities: parallel and serial. The specific requirements for equations' use are not set as in ISO 9920, e.g. uniform heat loss or surface temperature. The parallel method is defined similarly to the global in ISO 9920. Thus, the calculation methods' definitions in the standards differ.

EN 342, EN 14058 and EN 13537 for testing cold protective clothing or equipment refer to the methods in EN ISO 15831. Calculation of insulation by any method or using the average insulation of both methods is allowed depending on the test results with reference calibration ensembles. However, several issues need to be considered when using serial method.

EN 511 Protective gloves against cold gives its own equation assuming that the whole hand is just one zone. In the case of one zone the serial and the parallel model give the same result. More zones increase the insulation difference between the methods. With uniform surface temperature (required by EN ISO 15831) the parallel method provides the same insulation value with any number of zones while the serial method provides higher value with more zones compared to one zone.

EN 342 (cold) and EN 14058 (cool) use the same measuring principles and the same calibration garments. In the case of evenly distributed insulation, the differences in serial and parallel methods are relatively small, and proportional. However, with more insulation layers overlapping in heavy cold protective ensembles the differences increase, and don't follow the linear relationship any more. The calibration ensembles are selected to represent proper cold protective garments. Thus, if a garment piece does not represent a proper cold protective ensemble (faulty design, manufacturing error) the calibration does not have to be valid.

Lately a study on insulation measurements with electrically heated vest was presented. The vest provided an additional 10 W totally to torso region, and turned results from serial method to impossible 83 clo. It may be argued that manikin test is not meant to measure clothing with auxiliary heating. However, what happens if components of an ensemble do employ smart textile technology? A standard should avoid allowing any unrealistic results.

EN 13537 Requirements for sleeping bags utilizes the physiological model that has been developed assuming serial values to be correct. It works with properly manufactured sleeping bags. It would be a considerable work to replace the method, although, equally good models are available. Such a major change requires participation from several labs in and outside of Europe.

COMMISIONING OF A WATER CALORIMETER FOR USE IN THE CALIBRATION OF SUBMERSIBLE THERMAL MANIKINS

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In recent years, there has been increased interest internationally to investigate the equivalency between thermal manikins and humans, with the objective to use thermal manikins to assess the thermal properties of protective clothing, such as immersion suits. To conduct such research systematically, it is necessary to first establish a common, traceable calibration for thermal manikins, so there is confidence that thermal manikins accurately measure temperatures and heat loss and that differences in results among thermal manikins can be understood, quantified and accounted.

NRC-IOT has commissioned the construction of an environmental chamber to house a constant pressure water calorimeter donated by DRDC. The environmental chamber has dimensions of approx. 6m x 6m and has an exterior air handling unit capable of maintaining air temperatures over the range $5^{\circ}C – 25^{\circ}C$ within $0.5^{\circ}C$. The chamber control system is also capable of using the calorimeter water temperature as a setpoint to maintain a constant temperature gradient between the air and water. The dimensions of the calorimeter are approx. 2.2m x 0.9m x 1.2m and can contain 1100 litre of water. A mesh cradle allows the thermal manikin to be fully submerged in a prone position. A dedicated data acquisition system has been constructed to acquire the data from the following sensors. Two(2) precision thermistors to measure the chamber air temperature, two(2) humidity sensors to measure the chamber humidity, ten(10) precision thermistors to measure the well stirred calorimeter water temperature. Stirring is produced by a series of externally powered impellers capable of achieving an isothermal condition within 10 minutes of activation.

From the change in temperature of the water over time and its mass, the heat input from the manikin can be calculated. Allowance is made for the heat required to raise the temperature of the calorimeter's internal components (e.g. metal walls, mesh cradle, etc) and the manikin itself, the energy introduced by the impellers as well as the dry and the evaporative heat loss to the environment and the change in specific heat capacity of the water. The calorimeter is mounted on a force balance with a counter weight system. This allows a low capacity (hence high sensitivity) load cell to be used to measure the mass of the water to within 25 grams. Validation tests on the calorimeter were performed using a calibrated power source. Several tests confirmed the accuracy of the calorimeter to a few tenths of a percent. The sensitivity of the measurement is estimated to be approx. 1-2 watts.

CALIBRATION OF A SUBMERSIBLE THERMAL MANIKIN USING A WATER CALORIMETER

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The ISO Thermal Manikin Working Group completed recently a round robin exercise among 5 submersible thermal manikins from different laboratories to measure the thermal resistance of two standard immersion suits. The results from this exercise showed significant differences in the thermal resistance values among the manikins. Although some of the difference could be explained by methodological variability between laboratories, it is possible that the calibration of the thermal manikins could be responsible for some of the observed differences. The objective of the present study was to calibrate one of the submersible manikin used in the round robin exercise with a recently commissioned water calorimeter at NRC-IOT.

The manikin used in this study was a 71kg aluminum shell submersible thermal manikin (NEMO model; Measurement Technology Northwest, USA) with 23 independent thermal zones. Four calibration tests were conducted in the well stirred 1100L water calorimeter set at an average temperature of 12.2 ± 1.5°C. The air temperature surrounding the water calorimeter was set at a similar temperature (13.5 ± 1.7°C) to minimize the heat exchange with the calorimeter. The manikin was tested unclothed and its skin temperature was maintained at a constant and uniform temperature (0.3 to 2.8°C) above the water temperature for all of the 23 segments (tests 1-3) or at a constant power (test 4; 530W/m^2). Each of the calibration test lasted about 10 hours: 2 hours of a pre-tare period followed by a 3-4 hours calibration test and ending with a 3-4 hours post-tare. During the pre and post-tare periods, the manikin's power was turned off and the stirring system of the calorimeter, in addition to the chamber's temperature control system, were functional. The objectives of the pre and post-tare periods were 1) to establish the heat exchanges between the water calorimeter and its environment (baseline), and 2) to ensure that the heat accumulated in the manikin was fully transferred to the water.

During the calibration tests, the manikin power was turned on and varied (except for test 4) to maintain a constant skin temperature above the water temperature. During each calibration test, the power produced by the manikin and the heat transferred to the water calorimeter by the manikin were continuously monitored. The heat transferred to the calorimeter was estimated from the increase in the water temperature corrected for the heat exchanges with its environment. The water temperature increased by 1.7 to 2.9°C during the calibration test periods depending on the power to the manikin and the duration of the test. The calibration of the water calorimeter against a calibrated power source confirmed the inaccuracy of the calorimeter to be no more than a few tenths of a percent. The results from the calibration tests showed that the power generated by the thermal manikin was off by an average of 1.03 ± 0.64% compared to the power measured by the water calorimeter. In conclusion, the calibration tests performed on a submersible thermal manikin showed that the power measurement is accurate to about 99%.

DEVELOPMENT OF EMPIRICAL EQUATIONS TO PREDICT SWEATING SKIN SURFACE TEMPERATURE FOR THERMAL MANIKINS IN WARM ENVIRONMENTS

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Clothing evaporative resistance is one of the most important parameters for clothing comfort. The clothing evaporation resistance can be measured on a sweating guarded hotplate, a sweating thermal manikin or a human subject. The sweating thermal manikin gives the most accurate value on evaporative resistance of the whole garment ensemble compared to the other two methods. The determination of clothing evaporative resistance on a thermal manikin requires sweating simulation. This can be achieved by either a pre-wetted fabric skin on top of the manikin (TORE), or a waterproof but permeable Gore-tex skin filled with water inside. The addition of a fabric skin can introduce a temperature difference between the manikin surface and the sweating skin surface. However, calculations on clothing evaporative resistance have often been based on the thermal manikin surface temperature.

A previous study showed that the temperature differences can cause an error up to 35.9 % on the clothing evaporative resistance. In order to reduce such an error, an empirical equation to predict the skin surface temperature might be helpful. In this study, a cotton knit fabric skin and a Gore-tex skin were used to simulate two types of sweating. The cotton fabric skin was rinsed with tap water and centrifuged in a washing machine for 4 seconds to ensure no water drip. A Gore-tex skin was put on top of the pre-wetted cotton skin on a dry heated thermal manikin 'Tore' in order to simulate senseless sweating, similar to thermal manikins 'Coppelius' and 'Walter'.

Another simulation involved the pre-wetted fabric skin covered on top of the Gore-tex skin in order to simulate sensible sweating. This type of sweating simulation can be widely found on many thermal manikins worldwide, e.g. 'Newton'. Six temperature sensors (Sensirion Inc, Switzerland) were attached on six sites of the skin outer surface by white thread rings to record the skin surface temperature. Twelve skin tests for each skin combination were performed at three different ambient temperatures: 34, 25 and 20^{o}C.

Two empirical equations to predict the skin surface temperature were developed based on the mean manikin surface temperature, mean fabric skin surface temperature and the total heat loss. The prediction equations for the senseless sweating and sensible sweating on the thermal manikin 'Tore' were T_{sk}=34.0-0.0146HL and T_{sk}=34.0-0.0190HL, respectively. Further study should validate these two empirical equations, however.

COMPARISON OF EVAPORATIVE RESISTANCE USING THE THERMISTOR ON THE WET SKIN AND THE SHELL IMBEDDED WIRE TEMPERATURE SENSOR

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We measured the sweat skin temperature by thermistor and compared the temperature and evaporative resistance measured by imbedded temperature sensor in the manikin shell. The accurate measurement of the skin temperature was important to know the basic parameter of thermal resistance or evaporative resistance of clothing.

In many manikins, the skin temperature is measured by temperature sensor imbedded in the manikin shell. Though imbedded sensor is very convenient for measurement of clothing, the temperature measured by imbedded sensor is not the real skin temperature for wet conditions. Then we measured the skin temperature on the wet sweat skin and compared it with the temperature measured by imbedded sensor.

We used NEWTON (Measurement Technology NW, Seattle) for measurement which has the imbedded temperature sensor in each zones. We measured the evaporative resistance of business suits plus socks and shoes under isothermal conditions while the manikin stood still and was walking at 15, 30 and 45 steps/min. The room temperature and humidity were set to 34°C and 50%, respectively. The heat flux of the thermal manikin was controlled by software so that the skin temperatures measured by imbedded sensor were stabilized at 34°C for each zones. We put 4 pieces of thermistor on each zones and averaged the measured temperatures to calculate the mean skin temperature of the zone. The place of the thermistors had been decided so that the mean temperature measured by the thermistor was close to the mean of the skin temperature of the zones. The mean skin temperature of manikin was calculated by weighting the zone skin temperature with zone area except head, face and hands.

The measured skin temperatures of zones were lower than the setting temperature of shell sensor except foot zones. When the manikin walked faster, the mean skin temperature of manikin measured by thermistor decreased. Evaporative resistance calculated by imbedded sensor was larger than that by thermistor about 6% in standing. The two evaporative resistances and the ratio of evaporative resistance by thermistor to that by imbedded sensor decreased as the walking speed increased.

MEASUREMENT OF MOISTURE TRANSPORT AND ACCUMULATION PROCESSES INSIDE 3-DIMENSIONAL CAR SEAT AND UPHOLSTERY CONSTRUCTIONS WITH A SITTING SWEATING MANIKIN

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Introduction: The automotive and furniture industry requires sophisticated measurement and evaluation methods for the development of products like car seats or upholsteries offering a high climatic seat comfort. For this reason the Hohenstein Institutes operate several laboratory measurement devices like the Skin Model or an upholstery tester. It is used to measure physiological properties of single components (cover, lining and cushion materials) of car seats or upholsteries, of three-dimensional component combinations or of complete furniture constructions. In addition to existing testing methods a sitting sweating manikin was recently developed for the measurement of moisture transport and accumulation processes inside three-dimensional car seat and upholstery constructions. The physiological properties are important for the comfort level of a sitting person, or driver, to improve their efficiency and concentration.

Method: The sitting sweating manikin is a laboratory measurement device consisting of a three-dimensional measuring unit, water supply, sensor equipment, load frame and software to activate and to control the manikin. As water supply acts a multi-channel pump which delivers water in rates up to about 90 g min^{-1} to in total 16 sweat glands distributed all over the measuring unit's surface. The sitting sweating manikin is placed in a climatic chamber to simulate and control typical climate conditions prevailing in vehicles or buildings (temperature T_a from 10 to 30°C, relative humidity RH_a from 25 to 65%). The physiological investigations comprise 20 single components of car seats and upholsteries classified according to their function, material and construction. For the investigations the single components are arranged to in total eight combinations consisting each of a cover material (artificial leather, leather, textile), and/or a lining material (with or without SAP) and a cushion material (spring core, foam).
The amount of the sweat input is adjusted to 6 g m^{-2}, 18 g m^{-2} and 90 g m^{-2}. The ambient climatic conditions are set to 25°C and 30% relative humidity and the test duration to 120 minutes. Temperatures and relative humidity inside the combinations are measured at three characteristic areas, namely at the contact area between measurement unit and cover material (T_m, RH_m), upside the lining material (T_{u1}, RH_{u1}) and upside the cushion material (T_{u2}, RH_{u2}).

Results: From the data obtained the effects of cover, lining, cushion material and the amount of the sweating input on moisture transport and accumulation processes inside the 3D-combination constructions will be analysed and finished in the next month. The results can be used by automotive and furniture industry for the physiological optimization of their products.

Acknowledgement: We are grateful to the Forschungskuratorium Textil for the financial support of the research project (AiF-No. 293 ZBG), which was funded by the German Ministry of Economy and Technology via grants of the Arbeitsgemeinschaft industrieller Forschungsvereinigungen (AiF) Otto von Guericke.

DEVELOPMENT OF A MANIKIN SKIN SIMULANT FOR USE IN THE MAN-IN-SIMULANT-TEST

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The Textile Protection and Comfort Center's newly constructed Man-In-Simulant-Test (MIST) Chamber provides the capability to evaluate the resistance of personal protective ensembles against chemical threats. One opportunity for advancing MIST technology is the incorporation of an instrumented manikin testing capability. A significant technical challenge associated with development of a MIST manikin is the discrepancy between the MIST results for manikins and human subjects. The accepted theories suggest that since the manikin surface is non-porous any simulant vapor that enters the protective equipment will be adsorbed onto the detection pads which can lead to a lower protection factor for the garment in the MIST evaluation. In the case of human subjects, the detection pads adsorb some of the simulant while the individual's skin can also adsorb the simulant resulting in a higher protection factor. The main goal of this research is to develop a skin simulant for the manikin that will produce results consistent with the human subject testing.

The first phase of the research covers the design, construction, and validation of a lab scale MIST chamber. The chamber dimensions have been developed specifically to allow the monitoring of a manikin arm or the arm of a human subject. The most critical part of the chamber development has been the ability to introduce and control the concentration of the simulant, methyl salicylate (MeS), at the 100 mg/m^3 (16 ppm) set forth in the ASTM standard (F 2588). A gas cell FT-IR has been proven to accurately monitor the simulant vapor at the desired levels.

Through the use of the lab scale MIST chamber, it is possible to experiment with various fabrics and materials to determine their adsorption rates and total MeS adsorption. Not only can different materials be studied, but the Passive Adsorbent Dosimeters (PADs) used in the MIST analysis can be investigated to determine the effect of their surroundings on the simulant uptake rates. The ultimate goal of the research is to produce a garment which can serve as a second skin to make the manikin data agree with the human subject testing, or to eliminate variables, such as hair or PAD placement, between different sets of human subjects.

DEVELOPMENT OF ROBOTIC THERMAL MANNEQUIN FOR EVALUATION OF INDIVIDUAL PROTECTIVE ENSEMBLES

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An advanced robotic thermal mannequin system is under construction to enhance the testing capability for Individual Protection Ensembles (IPEs). Following a 13 month design phase, a self-contained system has been developed, integrating a state-of-the-art chemical testing facilities and a first-of-its-kind robotic thermal mannequin to perform high-resolution testing of protective clothing and equipment under live chemical exposure conditions. The IPE Manikin System (IPEMS) will be a freestanding, self-balancing robot that will simulate human physiology for realistic tests of protective equipment in a controlled environment. In addition to walking, crawling and doing a variety of suit-stressing calisthenics, the robot will have regional control of skin temperature and perspiration rate to simulate human physiology and real-time undersuit detection sensors to quantify the presence and concentration of chemical warfare agents. The system is currently under construction, with scheduled completion in 2012.

DEVELOPMENT OF A THERMAL CHILD MANIKIN

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Introduction: Sleep comfort is significantly affected by the thermophysiological properties of duvets or sleeping bags. For assessing and labelling the sleep comfort they provide for adults there are different measurement tools available, e.g. the Hohenstein Quality Label "Sleep Comfort" or EN 13537. However, there exists no prediction method for children, although for adolescents a sound sleep is even more important than for adults. Because of differences in thermoregulation of children only a mere modification of the prediction model for adults is not applicable. That was the reason for starting a research project on children's duvets and for developing a thermal child manikin.

Method: The research project focussed on the improvement of the physiological performance of children's duvets.15 duvets with different filling material, filling weight and quilting were selected. With these duvets Skin Model measurements of thermal and water vapour resistance were performed. Starting point of the development of Charlene was the existing thermal adult manikin Charlie which fulfils the specifications of ISO 15831. Charlene represents a child aged 3 years (height 92cm, weight 14kg), and has a plastic body consisting of 6 segments (head, torso, upper arms, lower arms, thighs and lower legs). Each segment can be electrically heated and controlled separately. To possess the same emissivity as human skin, Charlene was painted matt black. Measurements of thermal insulation were performed in a climatic chamber at $T_a = 15°C$ and $RH_a = 50\%$ rh. The surface or skin temperature of manikin Charlene was set to $T_s = 31°C$.

Results: The material specific water vapour resistance R_{et} of the duvets measured with the Skin Model varied between 49.6 and 137.1 m^2 Pa W^{-1}, with material specific thermal insulation values R_{ct} between 0.456 and 1.128 m^2 K W^{-1}. Both quantities were proportional to the thickness of the tested duvets, but not to their weight. The thermal insulation of the duvets, effective for the child in practical use, measured with the manikin Charlene varied between 0.524 and 0.730 m^2 K W^{-1}. With three independent tests on each duvet the variance of thermal insulation was less than 4%. Furthermore, the comparison of the thermal insulation of the duvets, measured on the one hand with the child manikin Charlene and with the adult manikin Charlie on the other, showed a good correlation ($R^2 = 0.85$).

Conclusions: The thermal child manikin Charlene is a suitable physiological measurement tool, yielding meaningful results. With it the sleep comfort perceived by children underneath duvets can be predicted by apparatus measurements.

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APPLICATION OF THERMAL MANIKIN TO EVALUATE THE PHYSIOLOGICAL SAFETY OF PROTECTIVE CLOTHING

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Core temperature is a major indicator to judge the thermo physiological safety of the protective clothing especially when the human subjects are exposed to extreme conditions of heat or cold stress. As it is extremely dangerous to use human subject to evaluate the core temperature under the thermal stress, indirect methods have been used.

To evaluate the thermal insulation or protection of the clothing, clo or im have been most widely used. These values, however, cannot give us sufficient information for the thermo physiological safety of the clothing. For example, as the fire fighters are exposed to thermal environment prolonged period than they might expect, we need to determine the limiting time of the protective clothing to expose to heat stress.

In this study, using sweating thermal manikin, Walter (Hong Kong Polytechnic Univ. Hong Kong), time to reach to survival core temperature is measured. As protective clothing, two different types of fire fighter’s turn out gear were used. Metabolism was simulated by input power at three different levels. Environmental chamber (Jspec, Japan) was set at 40±1°C and 30±5% RH. Wind velocity was negligible. Radiation is not included.

Relationship between time to increase core temperature to a certain degree and the Rct, Ret, clo value and im is analysed. Various clothing systems and garments were compared.

MANNEQUIN FLAME EXPOSURE TESTS FOR EVALUATING PROTECTIVE CLOTHING

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Worker exposure to short duration fires is a potential hazard in the energy resource development field and in the operation of petro-chemical plants. Protecting workers from this threat is a moral obligation and a legal requirement. As a last line of protection against exposure to short duration fires, industrial workers wear clothing made from materials that do not support combustion and will effectively retard energy transferred from short duration fires, minimizing the potential damage to the skin of the wearer. In the work place it is common for the clothing to be worn continuously. Thus clothing that is light weight and comfortable, yet thermally protective, are required.

The design and development of effective clothing begins with screening processes of the fabrics. Different standardized bench scale tests are available for this purpose. The first is used to determine the flammability characteristics of fabrics and layers of fabrics, while the second is used to compare unsteady heat transmission characteristics of the fabrics and layers of fabrics.

Suitable fabrics are finally made into garments and tested on an adult sized mannequin. Two standard tests are available for this evaluation, ASTM F 1930 and ISO 13506. They are essentially identical in that the intensity of the exposure is common (average value 84kW/m^2), while the duration depends on the end use of the garment. For typical petro chemical industries, 3 second exposures are used, while 8 seconds and longer are used in evaluating structural fire fighting clothing. Laboratories can produce up to 20 second exposure durations.

The evaluation of garment performance is based on the predicted skin injury that would result from the exposure. The prediction of skin injury is based on limited, but carefully conducted experiments on the forearms of human subjects. The mathematical models developed to predict skin damage are relatively simple, yet capture all the features of the experiments. They can be applied for a range of conditions where skin damage may occur within 0.5 seconds to 120 seconds after the start of the exposure.

The paper will present full details of a typical mannequin fire generation system, an outline of the test methods, details of the skin injury prediction model and typical experimental results for industrial coveralls.

PYROHANDS: MANIKIN HANDS FOR MEASURING THE THERMAL PROTECTIVE PERFORMANCE OF GLOVES IN FLASH FIRES

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This paper describes the Pyrohands Fire Testing System, a newly developed instrumented hand manikin and fire exposure system designed to provide reliable data on the thermal protective performance of gloves in controlled fire exposures. This includes the predicted 2^{nd} and 3^{rd} degree burns and the distribution of burns to the hands. Current fire test manikin systems lack the ability to provide data on the thermal protective performance of gloves in high intensity flame exposures.

Development of the Pyrohands System required advances in instrumented fire testing technology. These developments include anthropometric manikin hand forms capable of surviving repeated exposures in intense fire environments. New thermal sensors were designed that are small enough to fit in the hand form and fingers, yet robust enough to endure repetitive fire testing. A skin burn algorithm was modified to account for the difference in the thickness of skin in the hands. Skin thickness values vary between the palm, wrist, and back of the hand and are different than those in the human torso.

The Pyrohands Fire Test System is a powerful new manikin system for measuring the thermal protective performance of whole gloves in controlled laboratory fire exposures. Testing confirms the utility of this laboratory testing system for comparing gloves made with different materials and designs. This new manikin system will contribute to improve thermal glove designs, reducing the severity of hand burn injuries to those at risk.

A NUMERICAL MODEL FOR INTRUMENTED MANNEQUIN FLASH FIRE EVALUATION SYSTEM – A PARAMETER STUDY TO IMPROVE GARMENT PROTECTIVE PERFORMANCE

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Instrumented mannequin flash fire evaluation system is designed to assess clothing thermal protective performance against intense heat and flame hazards. It consists of three main components: flash fire simulation system, mannequin and sensor system, and system control and burn prediction system. The manikin is instrumented with more than 100 individual heat flux sensors distributed over the surface of his body. In addition to measuring the heat transfer to the manikin with exposure of the test garment or protective clothing ensemble, these sensors also set the exposure level by directly exposing the manikin to the flames in a test without the garment. The test specimen is placed on the manikin at ambient atmospheric conditions and exposed to the flash fire simulation with controlled heat flux, duration, and flame distribution. The incident heat flux measured by the sensors, during and after the exposure, is used to calculate the changing temperature of human tissue at two skin depths, one representing a second degree burn injury point and the other a third degree burn injury point.

A computer system controls data acquisition, calculation of surface heat flux, calculates skin temperature distribution histories, and predicts skin burn damage for each sensor location. The computer produces a full report of the test including a contour mapping of burn locations.

A numerical model has been developed to simulate heat transfer through a protective garment worn by an instrumented mannequin exposed to a laboratory controlled flash fire exposures. The model incorporates characteristics of the simulated flash fire generated in the chamber and the heat induced changes in fabric thermo-physical properties. The model also accounts for clothing air layers between the garment and the mannequin. Parameter studies were performed with the established numerical model to study the effects of varying thermal properties of garment material, garment fit and design as well as boundary conditions overall clothing protective performance.

The effect of fabric physical properties, such as fabric thickness, porosity, surface emissivity, was described and compared in this paper, along with the discussion how these prediction results can contribute to material and garment design to achieve maximum thermal protective performance. Additionally prediction results from the model demonstrate the air gaps existing in protective garments play a vital role in providing thermal insulation when exposed to flash fire conditions. Under the lab simulated flash fire conditions, an optimum range of air gap size was summarized.

OPPORTUNITIES AND CONSTRAINTS OF PRESENTLY USED THERMAL MANIKINS WHEN USED FOR SIMULATION OF THE HUMAN BODY

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Thermal manikins are the most advanced devices for clothing measurements due to their anatomic shape and their ability to sweat and move. These versatile evaluation instruments are nowadays implemented in a wide range of disciplines including clothing research and manufacturing, automobile industry, and the environmental engineering of artificial microclimates for human occupancy.

Presently, manikins are usually operated at uniform steady-state surface temperatures and homogenous sweat rates in comparative measurements, for example according to standards, such as ASTM F 1291-05:2005, ASTM F 1868-02:2005, ISO15831:2004 and ISO9920:2007. Nevertheless, various attempts have been undertaken to mimic the thermal response of a human more realistically, for example, by setting uniform heat fluxes to simulate different work loads, or non-uniform surface temperatures over the body, such as cooler hands and feet (McCullough, 2002; McCullough *et al.*, 1985), or uniform surface temperature change over time (Tanabe *et al.*, 1994). These attempts indicate the growing interest in using manikins to adequately simulate human thermal behaviours (body core and skin temperature distribution, onset of vasomotor reactions, sweating and shivering). Ideally, a new-generation manikin should ‘feel’ and respond dynamically to the thermal environment as real humans do that can be achieved by controlling it using mathematical model of human thermoregulatory system. Forerunners of such systems have been already developed for evaluation of the comfort in vehicles (Farrington *et al.*, 2004) and/or for testing clothing and sleeping systems (Psikuta *et al.*, 2008).

This project aimed to determine opportunities and constraints of the existing thermal manikins with regards to their functionality when controlled by a mathematical model of human thermal physiology. The thermal characteristic of each manikin included in the study was determined using the same measurement setup and measurement method for better consistency. The measurement protocols addressed the specific aspects of manikin performance when it is controlled dynamically. These included the method and the measurement uncertainty of the heat flux released from the sectors of the manikin (including heat flow between manikin body parts), and the response of the sector and its dedicated control system to the frequent change of the set-point temperature (reaction during heating and cooling, dynamic response to the step changes of the surface temperatures that are typical when using physiological model for control).

IMPLEMENTATION OF THERMO-PHYSIOLOGICAL CONTROL ON A MULTI-ZONE MANIKIN

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In many situations, especially for sport, thermal and evaporative resistance of the clothing are not sufficient to describe, understand or predict thermo-regulation and comfort of the end-user. Main sources of discomfort like water accumulation and post-exercise chill need to account for the strong interaction between environment, clothing and human body, and consider them as coupled systems in a dynamic time-dependant process. State-of-the-art manikins are constructed for operating in steady-state conditions, typically measuring resistances, and there is a need for thermal manikins reacting in real-time like a human body (skin temperature and sweat rate). This paper presents how we addressed the challenge of implementing a multi-segment thermo-physiological model to control a commercially available multi-zone manikin.

The PC controlling the manikin has three distinct software running simultaneously: 1) the native manikin monitoring software (36 zones) 2) a thermo-physiological model (7 segments) 3) our supervision software handling communication between both. The manikin software permanently reads from an input file the set-points for skin temperatures and sweat rates of all zones, adjusts the heating power to match the skin temperature set-points and writes in an output file the heating power of each zone.

The physiological model periodically reads from an input file the skin heat flux measured by the manikin on all body segments, simulates physiological response of the human body (temperature and sweat rates) and writes in an output file the core temperature, skin temperatures and sweat rates of each body segment. The supervision software converts the geometry either ways between manikin and physiological model (as number and definition of zones are different), converts heating power from manikin into skin heat flux, and paces data exchange.

Providing skin heat flux to the physiological model is the most challenging task. Present generation of manikins only provides the heating power delivered by the temperature controller to match skin temperature set-point. In steady-state conditions heating power equals skin heat flux but in transient conditions, due to controller response, the discrepancy may be huge (up to 10 fold). This is handled by considering each manikin zone as a heat capacity (pre-determined by specific experiment) and back calculating skin heat flux out of the heating power and skin temperature derivative. Adequate pre and post filtering (frequency, phase) are added to provide acceptable skin heat flux even in strong transient situations; filtering parameters are tuned for best comprise between stability and short time response.

When exposed to transient conditions, cold or hot, our system matches the expected physiological response within 1 min. The software is versatile and can accept any manikin and any physiological model, provided they use the pre-defined format for input/output data files.

THERMOREGULATORY MANIKINS ARE DESIRABLE FOR EVALUATIONS OF INTELLIGENT CLOTHING AND SMART TEXTILES

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Thermal manikins have been used to measure thermal properties of clothing. The use of thermal manikins has made a step forward in terms of quantifying thermal properties of clothing in a 3-D manner compared with the use of hotplates for material testing. The effects of clothing properties measured on the thermal manikins under steady state (constant manikin surface temperature and constant environmental condition) have usually to be validated by human subject tests. The thermal insulation and evaporative resistance values measured in the constant conditions are also used in modeling to calculate heat balance, predict human thermal physiological responses, and thermal comfort.

However, in many real life situations, clothing properties (e.g. moisture transfer), in particular the clothing properties with smart materials, e.g. phase change materials (PCMs), environmental conditions, sweating rate, skin temperatures are neither constant nor uniform. These make mathematical modeling complicated to take into account various transient, non-uniform conditions, and changeable properties of smart clothing which is becoming increasingly popular (Tang and Stylios 2006). Moreover, skin and core temperatures rather than heat loss or storage are commonly used to evaluate thermal comfort, define hypothermia and hyperthermia and evaluate heat strain. Therefore, the direct prediction of thermophysiological responses (skin and core temperatures) based on manikin measurements are valid (Psikuta and Rossi 2009), and could be considered another step forward towards direct evaluation of human-clothing-thermal environment interactions.

In the case of measuring a personal cooling system, current standard specifies the measurement of the average heat removal rate from a sweating heated manikin (ASTM F2371-10). This heat removal rate is not constant for the PCMs.

The objective of this study was to investigate the gap between the measured heat removal rate of smart clothing with PCMs obtained on a thermal manikin in a stable state, and clothing effects on local human skin and on core temperature, to compare the difference of the results obtained from both methods, and to highlight the need for developing intelligent thermoregulatory manikins.

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

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Ongoing experiments have been performed to validate the performance of Newton thermal manikin operating under physiological control. The integrated manikin + model system emulates the human thermoregulation system based on the Fiala model, and incorporates the local and global comfort prediction from UC Berkeley.

A set of experiments were performed to compare the response characteristics of the Newton + model system against human subject data sets obtained during wear trials of firefighter turnout gear. In a series of previously run tests, eight (8) male subjects were monitored for skin and core temperature during a sequential work + rest cycle. The metabolic work rates for subjects were calculated based on walking speed and treadmill inclination and input into the Newton system to replicate the same workload profile. During rest periods, the manikin was moved to a similar posture and garment condition as the test subjects.

Two key conclusions were established from this work. First, good agreement was achieved between manikin and human subject core temperatures. Core temperature increased in the manikin at a slightly higher rate than in the comparable human subjects. Agreement of skin temperature was excellent, with some variation in the face and upper arms directly 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 far exceeded human subject results.

A COMPARISON OF HEAT LOSS MEASUREMENTS ON MANIKINS AND HUMANS WEARING DRY IMMERSION SUITS

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The use of manikins to evaluate the thermal protection characteristics of cold water protective suits such as marine abandonment or helicopter passenger suits is not widely accepted in international standards. A full demonstration of the validity of such use requires that two questions be answered.

1. Is heat loss from a manikin representative of heat loss from a human in identical conditions?
2. Can the measured heat loss be related to the fall in core temperature of a human subject by appropriate models or correlations?

As part of a study of the first question, the heat losses, expressed as local heat transfer coefficients or local insulation values, were compared for two thermal submersible manikins and two human subjects wearing dry immersion suits with three different levels of closed cell foam insulation in two floatation positions in stirred water. Both the manikins and the human subjects were instrumented with heat flow sensors, skin temperature sensors, and outer suit surface temperature sensors at 13 sites over the body. Measurements were taken over the last 30 minutes of a 60 minute exposure in a water temperature of about 12°C and an air temperature which was in the range 15 to 19°C. In addition to the heat flow sensor readings, the heat loss from the manikins was determined by their sectional power consumption with their skin temperatures set to a uniform 30°C.

Floatation positions were vertical with immersion to the neck, and a natural position determined by the buoyancy characteristics of the suits. This latter position was determined by measuring the height of several body points relative to the water surface on the human subjects and then arranging the manikins to the same position. The human subjects were selected to have a similar fit with the suits as the manikins. The local heat transfer coefficients showed considerable scatter, but no systematic variation from manikin to human or from heat flow sensor to manikin power measurement could be discerned. When the local values were used to calculate an overall resistance by the parallel method, the scatter was greatly reduced, but again no systematic variations could be discerned. The final spread in the values of overall resistance was about +/- 18%. The differences between manikin and human (+/- 12%), between humans (+/- 13%), and between manikins (+/- 6%), were all of comparable magnitude. The trend of resistance as a function of suit thickness was similar to that shown by measurements of the insulation of the suit materials on a hot plate. It is likely that the variation in local heat transfer coefficients was due to the effects of differences in fit, folds or wrinkles in the suit materials, and was essentially random. These random differences then tended to average out in the calculation of the overall resistance. It is concluded that within the scatter due to fit, folds and wrinkles, the heat loss from the manikins was a good representation of the heat loss from humans for the vertical and natural floating positions in water for suits insulated with closed cell foam.

EVAPORATIVE RESISTANCE AND THERMAL INSULATION OF CLOTHING UNDER DIFFERENT POSTURE POSITIONS

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Evaporative resistance and thermal insulation of clothing are important parameters in the design and engineering of thermal environments and functional clothing. Past work on the measurement of evaporative resistance of clothing was however limited to the standing posture with or without body motion. Evaporative resistance of clothing when the wearer is at sedentary or supine posture and how it is related to that when the wearer is at standing posture are lacking.

This paper presents original data on the effect of postures on the evaporative resistance of clothing, thermal insulation and permeability index, based on the measurements under three postures, viz. standing, sedentary and supine, using the sweating fabric manikin-Walter.

Regression models are also established to predict the evaporative resistance and thermal insulation index of clothing under sedentary and supine postures from those under standing posture with high accuracy.

A PRACTICAL METHOD FOR DETERMINING CONTACT AREA DIFFERENCES BETWEEN HUMANS AND THERMAL MANIKINS SITTING IN INFLATABLE LIFERAFTS

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Accurately measuring heat loss from humans in cold environments and survival situations, such as sitting in a liferaft at sea, can be a difficult undertaking, considering the ethics and logistical issues involved. For this reason, there are significant benefits to be gained by using a thermal instrumented manikin, as long as the manikin's heat loss is representative of what would be expected for humans under the same conditions. Some obvious differences exist between humans and manikins that require the application of corrections to measured manikin data. For example, it has been demonstrated (Mak et al., 2009) that accounting for simple behavioural differences such as the regular shifting of one's position during the conduct of human tests can be quantified and applied as a correction to manikin test data. In addition to behavioural corrections, if the manikin is in a seated position, the rigid nature of its posterior surface causes the total area in contact with the seating surface to be underestimated when compared with a human. Hence, the manikin would underestimate the rate of heat loss when compared with that for humans under the same conditions.

This paper outlines the practical aspects and results of an experiment that was conducted to determine a correction for the contact area of a manikin seated in a liferaft. Human subjects and a thermal manikin were seated individually in a liferaft. The liferaft was floating on a calm, fresh water surface. A thermal imaging camera was used to capture video from a fixed position above the liferaft. This video record provided an indication of the relative temperature of objects in its field of view in differing shades of grey (i.e. warmer areas were whiter and cooler areas blacker). The manikin and subjects were seated for a period of time sufficient to transfer heat, through conduction, to the liferaft floor. After a suitable duration, subjects (or the manikin) were moved from where they were seated and the thermal camera recorded the shape of the heated zone left on the floor. Still images were captured from the video a few frames after the subjects had moved and were used, along with calibration details for the camera and image processing software, to determine the area in contact with the liferaft floor. This procedure was repeated for a variety of seating positions. It was found that, on average, 33% of the manikin posterior surface was in contact compared with 50% for the human subjects. This work was carried-out as part of a larger 3 year, multidisciplinary investigation of thermal protection in inflatable liferafts.

EVALUATION OF VENTILATION AND THERMAL PROTECTION REQUIREMENTS IN LIFEBOATS WITH A THERMAL MANIKIN AND MATHMATICAL MODEL

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Lifeboats are used as a means of evacuation from offshore structures and marine vehicles. Currently, the International Maritime Organization (IMO) Lifesaving Appliances (LSA) Code does not specify thermal protection and ventilation criteria for lifeboats.

The objective of the present study was to assess the thermal protection and ventilation rate of lifeboats for the Arctic environment. Two SOLAS approved lifeboats were used for model development: a 72-person lifeboat with engine off and a 20- person lifeboat with engine on.

The dilution experiments (where the rate of reduction of concentration in injected carbon dioxide was estimated, to determine ventilation rate) with the 72-person lifeboat found that the lifeboat had a ventilation rate of 2 l/s with vents open, which is inadequate to maintain carbon dioxide level below 5000 ppm. The 20-person lifeboat had 11.6 l/s at full engine power and 7.8 l/s at half power; both being inadequate ventilation rates.

A thermal manikin and a mathematical model were used to assess heat and cold stress of lifeboat occupants under various lifeboat, occupancy and ventilation conditions in the Arctic summer environment. In a lifeboat with the engine running, the occupants are likely to suffer heat stress unless a ventilation rate of several hundred litres per second can be achieved.

The effect of occupant heat loss with ventilation was also assessed in the 72-person lifeboat with the engine off. When the lifeboat is carrying half the number of people for which it is rated and when these occupants are wearing dry reference clothing and lifejacket, the ventilation rate could be increased to 100 litres per second (minimum ventilation to keep carbon dioxide below 5000 ppm is 27 l/s) to achieve thermoneutral heat loss (51.7 W/m^2). When the lifeboat is fully loaded, the ventilation rate can be increased to 300 l/s to achieve a similar microclimate (minimum ventilation rate to keep carbon dioxide level below 5000 ppm is 54 l/s). A higher ventilation rate is required if the engine is on. This suggests that an increase in ventilation rate needs to be implemented to avoid heat stress and provide adequate ventilation.

In conclusion, the use of a thermal manikin supported by a simple heat loss model helped define the adequate ventilation rates in lifeboats under simulated Arctic summer conditions and showed that the risks are mainly carbon dioxide toxicity and heat stress.

(Poster Presentation)

COST-EFFECTIVE AND EASY-TO-USE SWEATING FOOT MODEL. DEVELOPMENT AND FIRST RESULTS

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A large variety of foot models are used in laboratories worldwide to simulate the physiology of the human foot as well as the interaction with footwear systems and to predict the climatic wearing comfort (Kuklane et al. 2005). Most of the recent manikins are divided into different sections with an independent heat and temperature control unit for each of these sections. The simulation of sweating is done by supplying water through tubes and holes distributed over the surface of the foot model or by using humidified air guided into the phantom (Kurz et al. 1999). All of these setups are fairly expensive due to the sophisticated technique and extended control systems for temperature, water and/or air supply. As a consequence these manikins are often not suitable as a routine method, for instance to accompany and control a running production line in the footwear industry. On that score it was the intention to develop a simple, innovative and cost-effective manikin for testing footwear systems (shoe and sock) concerning their water vapour transmission rate and global thermal insulation as the basic climate wearing comfort values (Rottenfusser et al. 2008). The functional principle of the introduced system called *Sweator* was inspired by setups like the *WBCT - whole boot comfort test* (W.L. Gore Associates 1990) and the sweating fabric manikin *Walter* (Fan et al. 2002).

Using the data of 3D foot scans a hollow-model with a defined perforation was developed and built-up by a laser-sintering procedure from a polyamide material. The model is equipped with an exchangeable membrane (water vapour permeable and water-tight material) coating inside or a water-vapour-tight liner, respectively, and a climate control unit consisting of a heat supply, pump unit and temperature sensor. Thus, the climate adjustable manikin can provide defined and reproducible heat and humidity quantities to footwear systems by simple control and regulation procedures. The complete setup is fixed on a balance which can be read-out together with the T/rh sensors at the manikin surface using a computer interface. Depending on the water vapour partial pressure difference and on the selected membrane inside the manikin, a water vapour transmission rate from the “nude” foot model up to 15 g/h can be achieved. Extended tests with a variety of different boots as well as wear trials with test persons are carried out as a basis for the validation and the comfort correlation of the *Sweator* setup.

(Poster Presentation)

COMPARISON OF MICROCLIMATE BETWEEN A BREATHABLE AND A NON-BREATHABLE SHOE

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Shoe climate is an important parameter of shoe comfort. It is defined by temperature, humidity, dampness and ventilation through the shoes as well as by the sensation of these parameters. Especially high humidity and temperature can lead to diseases like blisters and runner's feet. In sport less thermal stress leads to better performance. Hints could be found that better foot cooling can lead to a decline of heat stress, too.

Thirty experienced runners (age 33±10; 36±20km/week) took part in this study. Their 10 km-best was used to define an individual running speed for five different phases (sitting – running, moderate speed – running, high speed – running, moderate speed – sitting). Tests took place under laboratory conditions. Test shoes were an adidas ClimaCool shoe (breathable) with textile mesh upper and a varied version with synthetic upper material (non-breathable). In these shoes temperature and humidity were measured by sensors. Water absorption of the shoes was recorded as well as subjective feedback of temperature, dampness and comfort.
In addition measurements of thermal insulation (T_a=15°C, RH_a=50%rh, T_s=31°C) and water vapour resistance (isothermal, T_a=23°C, RH_a=25% rh, T_s=23°C) were performed with a moveable sweating foot. Values were measured standing and walking.

Measured temperature and humidity were always highly significant lower for the breathable shoe compared to the non-breathable one. Temperature and humidity rose in both shoes during running, but much more in the non-breathable one. Biggest temperature difference was about 3K and could be found in phase IV (moderate speed). Differences in humidity were up to 37% r.h. (phase IV). Water absorption was about ten times higher for the non-breathable shoe. Subjective feedback brought highly significant differences, too. Humidity and temperature were always perceived significantly lower in the breathable shoe. Thus, it was more often judged as climatically comfortable. Analyses of measurements with the sweating foot and correlations with the results from the running test are still in progress, but will be finished within the next months.

In wearer trials values of temperature and humidity were much lower in the breathable shoe compared to the non-breathable and subjects could feel these differences. This leads to the conclusion, that shoe climate can be approved by a breathable upper material.
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(Poster Presentation)

EFFECT OF LOAD, ITS DISTRIBUTION ON CLOTHING SYSTEM THERMAL PROPERTIES, AND PREDICTED HUMAN THERMAL RESPONSES

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In the design of load carrying clothing accessories, the sweating thermal manikin together with a thermal physiological model are efficient useful tools for quantifying the changes in heat flow properties of the clothing system affected by the accessory and heat strain experienced by the person carrying the load. An example described here is the evaluation of pack designs for carrying combat supplies and tools for a Warfighter. Manikin measurements following ASTM F 1291 procedures measured the dry and evaporative heat resistance values between the skin and the environment with the manikin wearing an Army combat uniform (ACU) and body armor (IBA) with: 1) no load or pack (ACU_IBA), 2) the current standard Army back pack (BP) that carries combat load primarily on the back and 3) a pack (DL) that carries the combat load distributed more uniformly about the torso.

The BP and DL packs increased the resistance to dry heat flow by 4.6 and 0.8% respectively over the no load condition. The resistance to evaporative heat flow decreased by 6.3 and 5.8% respectively with the BP and DL load carrying accessories. Further the total weight of the ensemble increased by 21 and 15.3 kg with the combat loaded BP and DL packs. The USARIEM Scenario-J thermoregulatory model was used to predict the effects of BP and DL on the Warfighter. At rest the model predicted no difference in body core temperature (Tc) and the Moran physiological strain index (PSI) between the ACU_IBA, ACU_IBA+BP, and ACU_IBA+DL clothing systems. PSI rates heat strain from 0→10 based on deviations in heart rate and Tc from resting thermally neutral levels. However when walking at 4.8 km/h the added weight of the BP and DL packs increased metabolism by 25% and 17% respectively and after 1 hour of steady walking in a 30°C and 41%RH sunny environment Tc increased over the no load condition by 0.7°C with BP and 0.5°C with DL loads. Further PSI increased from 6.2 with no load to 8.4 with BP and 7.9 with DL packs. Thus the manikin-physiological model combination indicates that the distributed load carrying design (DL) is an improvement for the Warfighter physiologically and human testing is warranted to assure successful deployment.

(Poster Presentation)

EXPERIMENTAL STUDY OF NON-UNIFORM THERMAL ENVIRONMENT AROUND HUMAN BODY USING A THERMAL MANIKIN

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The purpose of this study was to investigate the effects of non-uniform thermal environments on human body, caused by partial cooling or heating from local airflows, using a thermal manikin. The results are for mathematical simulation of such non-uniform situations. The thermal manikin method has some advantages compared with using a human subject, because it enables extended periods of measurement, the attachment of sensors firmly on the surface of skin or clothing, the elimination of body motion, and so on.

Two types of experiments were carried out; (I) the measurement of air temperatures and wind velocities very close to the skin or clothing surface of the human manikin, and (II) the calculation of total heat transfer coefficient from skin surface to ambient environment including the influence of clothing insulation, for each part of human manikin body. Thermal conditions of the room were preset at air temperature (Ta) 40 deg C and 10 deg C, like hot summer (Ta, 40 deg C; relative humidity, 50%) and cold winter (Ta, 10 deg C), respectively, and the blowing of cool or warm air to some body parts of the sitting manikin performed partial cooling or heating. In experiment (I), the results were compared with data from previous human subject experiments under the same situation and the validity of measurements was considered. In experiment (II), measured local skin temperatures of the thermal manikin, heat flux from the manikin and air temperatures close to the surface were used to calculate the total heat transfer coefficients by two different methods based on different assumptions. The results from the two methods were examined.

As a result of experiment I, differences of air temperatures and wind velocities very close to the surface between the body parts under partial cooling and warming conditions were verified, and the values from the manikin were found to be comparable with previous measurements on human subjects at similar ambient temperatures and conditions. As a result of experiment II, total heat transfer coefficients of the body parts individually calculated from two different formulas were of similar value except for a few case.

The results enable accurate numerical analysis by a thermoregulation model of the human body and evaluation of the effects of non-uniform thermal environments.

(Poster Presentation)

A PORTABLE CALORIMETER FOR THE CALIBRATION OF THERMAL MANIKINS

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Due to expanding activities in remote, cold environments such as resource development in the Arctic and new polar cruise routes, measurement of the thermal protection of garments and shelters is becoming critical to ensure the safety of crews and passengers in extreme conditions. Thermal manikins offer an alternative to the ethics of human subject testing; however, some manikin results have disagreed in a recent round-robin test. The source of the inconsistency between manikins could be methodological or calibration. Inconsistent measurements dilute the argument for using manikins in place of human subjects. Since manikins are not mass-produced and a variety of designs are in use, a calibration tool is needed to make manikin data credible and prove equivalence to human subject testing. Calibration by means of a standard clothing set can demonstrate consistency among manikins but not absolute accuracy. To facilitate the calibration of manikins in many locations, there is need for a portable calibration system.

The objective of this work is to develop a portable air calorimeter to test thermal manikins in their native environment (i.e. local control chambers, methods and equipment) with a theoretical accuracy of close to 1%. The calorimeter houses the manikin in a sealed air chamber stirred with a small fan to prevent stagnation and removes heat using water flow through aluminum tubing encased in sheet aluminum walls. The heat lost by the manikin is calculated from the temperature rise in the water and the mass flow rate. Accuracy is achieved by minimizing extraneous heat transfer with vacuum-insulated panels and a calibrated mass flowmeter (±0.2 g/s) and paired thermistors (± 0.01°C). The calorimeter will be calibrated against a standard before each use. The calorimeter is designed for shipping complete with the accessories (pump-reservoir system) and to operate inside a variety of facilities around the world, relying on universal power supplies, minimal set-up and only distilled water added by the user. The calorimeter is sized to fit a wide profile of the manikins currently in use in their own environmental control chamber.

(Poster Presentation)

THERMAL MANIKIN EVALUATION OF ENSEMBLE DESIGNS INTENDED TO REDUCE THERMAL BURDEN

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Military chemical and biological agent (CB) protective ensembles have traditionally been designed as heavy, fully-encapsulating garments intended to be worn over additional duty clothing. This study evaluated novel, lightweight ensemble designs to determine those with the highest evaporative cooling potential when measured on a thermal manikin (TM). This was strictly a design study. No garments were constructed from actual CB protective fabrics.

Two different design concepts were evaluated: one where CB protection would be incorporated in a separate undergarment layer to be worn under a duty uniform (CBUG); and one with CB protection incorporated in a single combat uniform (CBCU). CBUG designs included undergarment layers that were loose or tight fitting, constructed with thinner, ventilating panels at underarms, crotch, torso, and a T-shirt/bike short design. CBCU designs included four with active ventilation features (zippers, vents, valves) at the upper arms and thighs, three with spacer ventilating mesh at various locations around the torso/shoulders, one with ventilating panels and one with a conformable liner. Ensembles were tested on a TM during four tests: TM standing in low wind (0.4 m/s); TM standing in high wind (2.1 m/s); TM walking (3 mph) in low wind; and TM walking in high wind. Total evaporative cooling potential was defined as the ratio of the ensemble's permeability index to thermal resistance (i_m/clo), with higher values indicating reduced wearer thermal burden.

When averaged across all tests, there was no significant difference in i_m/clo between the CBUG and CBCU concept groups. CBUG group i_m/clo values ranged from 0.32 to 0.37, with the lowest value seen in the T-shirt/bike short design and highest in the ventilating panels design. CBCU group i_m/clo ranged from 0.29 to 0.37, with the lowest value seen in the conformable liner design and highest shared by three designs with active ventilation features. Increasing wind speed when standing increased i_m/clo by an average 55% (CBUG) and 68% (CBCU) compared to low wind values. Additionally, walking in low wind increased i_m/clo by 64% (CBUG) and 45% (CBCU) compared to standing in low wind. These TM results suggest that future CB protective ensembles could reduce thermal burden by utilizing both strategically-placed, lighter materials and active ventilation features located on arms and thighs of the garments. Also, the observed cooling benefits from increased air velocity over the body and basic body locomotion indicate untapped methods of increasing sweat evaporation within the microclimate of a CB ensemble. The next phase of this effort involves TM testing of hybrid versions of several of the above designs constructed with actual CB protective fabrics.

(Poster Presentation)

HUMAN ADAPTATION TO HEAT DURING EXERCISE

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Human adaptation to environmental conditions can be considered as different quantitative characteristics of thermoregulatory system. Mathematical models were developed for prediction of thermoregulatory events in man during exercise in hot dry environment. The purpose of this article is to evaluate the effect of threshold temperatures and proportionate thermoregulatory commands for skin blood flow and sweating for man in heat dry environment during exercise.

The computer tool is based on the complex of mathematical models for human physiological systems of man. The mathematical description takes into account the interaction of physiological variables and parameters that characterize participation of nervous, thermoregulatory, circulatory, water-salt, respiratory systems and others in adaptation processes. The models take into account exercise intensity, distribution in skeletal muscles, duration of exercise, environment (temperature, humidity and air velocity), and clothing. Modeling experiments demonstrate transient and steady state processes via core and surface temperatures, total and local sweat evaporation, evaporative and dripping sweat rates, total water losses of organism, wettedness and sweat efficiency, cardiac output and heart rate, skin and muscles blood flows and others.

Modeling results showed that the most effective impact on adaptation processes is the increase of proportionate thermoregulatory coefficients for sweating. This value can be considered as the main parameter that provides human adaptation to heat in rest and during exercise.

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(Poster Presentation)

COMPARATIVE STUDY OF VARIOUS UNDERGARMENTS UNDER A DRY SUIT USING AN IMMERSIBLE THERMAL MANIKIN

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Navy divers use Protective Combat Uniform (PCU) Combo under a dry suit to provide varying levels of thermal protection. The PCU is an interchangeable 15 piece, 7-level ensemble that is worn in layers appropriate for the mission. The goal of this thermal manikin study was to test various undergarments under the dry suit for thermal resistance (R_{ct}) or 'Immersed Clo' and to predict based on the Clo values whether the undergarments and the dry suit combination provides adequate thermal protection to survive for 12 hrs in 45^{o}F and 55^{o}F water.

Six different undergarments including some COTS (commercial off the shelf), an aerogel suit (jacket and trouser) and PCU Combo levels 2, 5, and 7 were tested under a hybrid dry suit. Some of the COTS undergarments consisted of different weights insulation made out of polyester and combinations of polyester and polyolefin. The study predicts that all the undergarments tested with the hybrid dry suit would give adequate protection to the divers in 55^{o}F water. The aerogel undergarment, which weighs approximately 6.85 lbs, provided similar Clo values compared to the PCU Combo layering system that weighs approximately 8 lbs. Only the PCU Combo and the aerogel suit are predicted to provide adequate protection to the divers for survival in 45^{o}F water. All the other undergarments under the dry suit are predicted to cause excessive drop in the diver's mean body temperature.

(Poster Presentation)

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

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Ongoing experiments have been performed to validate the performance of Newton thermal manikin operating under physiological control. The integrated manikin + model system emulates the human thermoregulation system based on the Fiala model, and incorporates the local and global comfort prediction from UC Berkeley.

Validation studies consisted of replicating the experimental process of Stolwijk/Hardy, Werner/Reents, and Raven/Horvath. These experiments bracket a wide range of experimental conditions, although the number of test subjects is limited. Conditions include steady state convergence of skin and core temperature at a thermoneutral state, plus warmer and colder ambient states. Transient validation experiments included step changes to warmer rooms and to colder rooms.

The agreement between manikin/model and historical data sets ranged from good to excellent, with the best agreement achieved on the thermoneutral-to-warm transitions, and the poorest agreement obtained for steady-state thermoregulation in 10 Deg C ambient temperature, and thermoneutral-to-very hot step changes. Possible justifications for these differences are presented and will guide future model optimization and validation work.

THERMAL MANIKIN EVALUATION OF PROTOTYPE ARM AND SHOULDER ARMOR

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Recent unpublished findings on ballistic armor that we are aware of suggested the viability of overlapped segmented soft armor. Similarly, recent research that we have performed showed the potential for using 3D spacer material within soft body armor to improve evaporative resistance. Specifically, this research identified two promising spacers which were used to design prototype body armor.

This experiment investigated using 3D spacer material within the structure of prototype soft armored sleeves to influence the armors' dry-thermal (R_{ct}), intrinsic thermal (R_{cl}), evaporative (R_{et}) and intrinsic evaporative (R_{ecl}) resistance. Wind speed was manipulated at two levels and lower arm microclimate temperature was measured between the uniform and prototype armored sleeves. Four prototype sleeves and shoulder units were designed as three piece units, that is, shoulder, upper and lower arm units. Spacer material was inserted into three prototypes, but not the control. Unidirectional Dyneema® was the ballistic material. R_{ct}, R_{cl}, R_{et} and R_{ecl} after three replications of all prototypes under two wind speeds was obtained using a thermal manikin manufactured by the Hong Kong POLYU. All tests followed ASTM F1291- 05 and ASTM F 2370 – 05 standards except for wind speed. Ambient temperature and humidity were 20 ±3°C and 50±3% respectively. Microclimate temperature was recorded using two temperature sensors located approximately in the middle of the forearms. To test the hypotheses, a factorial design with two factors was used. The first factor was prototype sleeve with four levels while wind speed with two levels (2 and 3 m/s) was the second factor.

None of the prototypes successfully reduced either R_{et} or R_{ecl}. In fact, all prototypes demonstrated increased R_{ct} and R_{cl} values compared to the control. R_{ct}, R_{cl}, R_{et} and R_{ecl} of the prototypes and the control were reduced as wind velocity increased, however microclimate temperature was not affected significantly.

We concluded that fit of the prototypes on the manikin, fabrication of the prototypes, and our mechanism for generating air movement could have influenced the results. This is reasonable given that Kunz and Chen (2005) in a human subjects study investigating the effect of a 3D woven hollow structure worn beneath a ballistic vest on ventilation, concluded that the developed 3D hollow woven structure provided an equivalent amount of ventilation (and in an extension heat release capability) with the natural ventilation that occurred inside the garment-body system caused by the wearer's movement. They assumed that fit in combination with the wearer's movement created sufficient ventilation in order to decrease the skin temperature in areas where the garment was loosely fit. An increase in skin temperature was observed only in areas in which the vest was well fitted to the body, such as the chest area.

COOLING CAPACITY DETERMINATION FOR BODY VENTILATION SYSTEMS

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The purpose of this study was to propose a method for determination of cooling capacity of a body ventilation system (BVS).

Cooling capacity was calculated as the cooling potential times cooling efficiency. The difference between enthalpies of the air entering and exiting the BVS was the cooling potential (i.e. the maximum cooling capacity). Enthalpy was a function of air temperature and humidity. The cooling potential was reached when the temperature of air exiting the BVS was equal to the skin temperature and the air vapor pressure was equal to the saturated pressure at the skin temperature. Cooling efficiency was defined as a ratio of cooling capacity to the cooling potential, and was determined through thermal sweating manikins. Therefore, BVS cooling capacities were calculated from the skin temperature, ambient temperature, ambient humidity, ventilation rate and cooling efficiency. A BVS system was evaluated on the manikin under environmental conditions of 25°C, 30°C, 35°C and 40°C, and relative humidity 25%, 50% and 75%, respectively. The manikin skin temperature and vapor pressure were set to 35°C and fully saturated.

The measured cooling capacities ranged from ~40W to 157W. Cooling efficiencies were 0.15 ± 0.01 and ranged from 0.13 to 0.16. This indicated that cooling efficiency can be considered constant, cooling efficiency determined under the ASTM test condition (i.e., 35°C and RH50%) can be applied to other conditions. The newly proposed method can be used to estimate BVS cooling capacity in physiology studies and to evaluate BVS effectiveness.

BIOPHYSICS OF BODY ARMOR ENSEMBLES AND THE IMPACT ON PREDICTED HUMAN THERMAL RESPONSES

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Lighter weight protective body armor (PBA) ensembles are being designed to reduce the physiological strain on soldiers. However, realistic predictions of physiological strain on soldiers must also account for the heavy loads soldiers typically carry (load bearing vest, electronic devices, battery, rifle, hydration system, etc.).

This study examined how weight reduction of PBA with or without full combat load affects overall biophysical clothing properties worn by a soldier and the simulated thermal responses. Thermal resistance (clo) and water vapor permeability (im) values of Fire Resistant Army Combat Uniform and PBA with full combat load (FRACU-full) (weight: ~70lbs) and PBA without combat load (FRACU-nold) (weight: ~30lbs) were collected on a thermal manikin using a standard test method (ASTM F 1291).

The physiological response of a simulated average US Army soldier (height: 177cm, weight: 82kg) was evaluated using a USARIEM thermoregulatory model. We simulated a heat acclimated soldier, wearing FRACU-full or FRACU-nold in addition to a t-shirt/briefs/wool socks walking at 1.34 m/s under the sun in warm-hot environmental conditions (i.e., 25°C, 35°C with constant dew point of 15°C). The thermal resistance for FRACU-full (clo: 1.52, im: 0.46) was higher than FRACU-nold (clo: 1.33, im: 0.44), although im (water vapor permeability) values for these two prototypes were similar. The heat production estimates of a soldier with FRACU-full and FRACU-nold were 463 and 385W, respectively. This difference is primarily due to the metabolic cost of carrying different loads. Using core temperature of 39°C as a safety threshold, the simulation results indicated that a soldier could tolerate heat for more than 240 min with or without full combat load when air temperature was 25°C. However, when air temperature was 35°C, the capacity for sustained work decreased for a soldier with full combat load to 90 min, or less than half the tolerance time of the soldier without full combat load (190 min). This means that the latest PBA system, with or without full combat load, allows sufficient evaporative heat loss when operational and environmental stressors are mild. However, when these stressors are high, reducing work time or combat load is needed to decrease/delay the thermal strain on soldiers.

The use of thermal manikins and thermoregulatory modeling provides a way to quantify the biophysical properties of integrated protective ensembles and their effects on thermal strain. This insight should lead to better decision making regarding material development and changes in doctrine.

CORE TEMPERATURE PREDICTION MODELING USING A SWEATING MANIKIN

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A smart clothing system was developed to monitor the wearer's vital signs by investigating the correlation between the ambient temperature and humidity and the core temperature of the wearer. When the core temperature approaches 39 ºC, the thermal regulatory mechanism of human s begin to malfunction and leads to heat stress, dehydration and even death (Reginald, 2008). This study was focused on military personnel and fire fighters because of the thermal environment and potential hazards that are posed. The sweating manikin, Walter, was used in a novel way to achieve a prediction equation between the core and the microenvironment.

Thermal sweating manikins are generally used to measure the thermal insulation of garment systems. However, in this study, the manikin was used in an unconventional manner, in order to simulate physiological changes in a human body at different core temperatures. This was achieved by setting the core temperature constant and recording the skin temperatures and other parameters. The manikin used in this study was a sweating fabric manikin, Walter® (Hong Kong) with skin temperature sensors placed at 15 locations. The environmental chamber (Conviron, Winnipeg, Manitoba, Canada) housed the thermal manikin and was set to keep the ambient temperature at 20±3ºC, and relative humidity at 50±3%.
The manikin was set at different core temperatures and dressed in treatment garment systems: either (1) battle dress uniform (BDU), or (2) commercially available fire fighter gear. Both garment treatments were modified by adding pockets at front and back of coats to hold the wireless microclimate sensors. Microclimate (MC), temperature and humidity were collected every 30 seconds by wireless sensors in addition to the data collected by the sweating manikin.

MC humidity was found to be unreliable and excluded from both studies. The steady state section of the testing was used for analysis for the military uniform and core temperatures were regressed on MC temperature and humidity over time. Data collected for 36, 37, 38 and 39°C were used to obtain core temperature prediction equation and a cross validity test was conducted using the rest of the data to evaluate the reliability of the equation. The section of the data between the time Walter reached 36°C to the time the target temperature was reached represented the heat transfer and metabolic heat gain as the core temperature raised from a normal 37°C to 38°C. For the fire fighter garment analysis, only the transitional data were used. Back MC temperature was not a significant predictor of the core temperature.

Prediction equations were evaluated to be a useful model in the 36-39°C range by the data collected by the manikin. To test the validity of the method described here, human subject testing was conducted using the exact conditions. The data analysis is being conducted.

COMPARISON OF THERMAL AND EVAPORATIVE RESISTANCE BETWEEN TWO GARMENT DESIGNS DRIVEN BY MATERIAL CHARACTERISTICS USING A THERMAL MANIKIN

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The Laboratory for Engineered Human Protection (LEHP) has developed prototype garments for the purpose of improving comfort while protecting warfighters against toxic chemical agents. This paper examines the difference in thermal and evaporative resistance of four LEHP designed garments. The garment design was driven by fabric characteristics (stretch versus non-stretch) and therefore resulted in two designs, one having a closer or tight fit to the body (design T) and the second having a loose fit (design L).

One comparison is made between designs T and L, each produced from two different fabrics: Material A (stretch fabric) and Material B (non-stretch fabric). A second comparison is performed between garments made from material A and a non-stretch material (material B) in same garment design, T or L. Earlier work revealed a significant difference in thermal resistance between design T and design L garments made with material A as well as a significant difference in thermal resistance between design L garments made with materials A and B.

The early research revealed that thermal resistance of a garment is influenced by material selection as well as garment design. This study examines the influence of material selection and garment design on evaporative resistance and draws comparisons to previously reported thermal resistance study using the same materials and garment designs.

FUNCTIONAL APPAREL DESIGN FOR THE HUMAN TORSO

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Over the years, much research has been done examining thermo-mechanical properties of the human under various environmental conditions. It has been shown in previous studies that humans do not emit heat or moisture uniformly, and many factors such as the ambient environment and a person's somatotype play significant factors in an individual's thermal flux. However, functional apparel is typically designed as if an individual's heat and moisture as uniform. Today, many innovative fabrics and finishes exist in the commercial market, but the same material or finish is typically used throughout the entire garment without consideration towards optimizing heat and moisture transfer based on an individual's thermal or moisture patterns.

This paper discusses procedures and results of ongoing research done to date at Central Michigan University involving over 760 human subjects exploring thermal profiles of the human torso. In this research, all 760+ subjects were scanned in a 3D body scanner, then four images of their torsos were taken (front, back, left and right) using an infrared camera. Following data collection, 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) thermal image pre-processing; (2) image registration; and (3) 2D/3D mapping. Challenges involving human subject testing will be presented. Results will show how the thermal profiles of the human torso can be categorized into several different "families" by using thermal contour maps and thermal variability compared.

Lastly, the paper discusses the future research objectives to explore the interaction of the apparel with the human torso on human comfort and functional performance, measuring and comparing existing next-to-skin apparel and garment systems with prototypes. Prototypes will be developed using a sweating guarded hotplate and a custom-built 46-zone NEWTON manikin system. The overarching objective for this research agenda is to apply human-centered design concepts to create prototype functional apparel systems which optimize heat and moisture transfer, while minimizing production costs.

CHALLENGES OF HUMAN THERMAL MODELING

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Thermal models are often used to predict human performance during exercise under various environmental conditions. An important factor in such predictions is the nature of clothing worn by subjects, which is usually determined using a heated and sometimes sweating manikin.

Human thermal models typically represent the body as a set of circular cylinders, although a few models employ finite-element methods that allow a more realistic geometric representation. The basic equation is the so-called bioheat equation proposed by H. H. Pennes in 1948. Given a reasonable geometric representation, we can assume that transient-state temperatures are computed with acceptable accuracy. Of greater concern are the approximations and assumptions made about basic physiological and physical processes. The principal purpose of this paper is to discuss some of those factors.

Important physiological factors include blood flow, especially cutaneous blood flow, shivering, sweating, and countercurrent heat transfer. Although regulation of skin blood flow involves at least four factors, central temperature, mean skin temperature, local skin temperature, and level of exercise, many models account for only the first two. Correlations for shivering are often based on data derived from rather extreme conditions, such as immersion in very cold water, and those correlations probably overestimate shivering metabolic rates during less severe exposures to cold. Sweating is also complex and quite variable among individual, depending on acclimatization to heat and physical condition.

Important physical factors are the thickness and distribution of subcutaneous fat, which is typically based caliper measurements, even though several studies have shown that such measurements can be 50 percent too low. Other important physical factors are transport of sensible heat and water through garments during exercise. Accumulation of water within garments owing to sweating and evaporation of water within garments following vigorous exercise represent real challenges to models. Energy transport through impervious garments in a cold environment is not well understood.

Improving thermal models requires good experimental data for human performance while wearing well-defined garments under carefully controlled conditions. In addition to calling attention to factors that need to be studies, it is hoped that this paper might stimulate such efforts in the future.

CHARACTERIZATION OF THE THERMAL AND EVAPORATIVE RESISTANCE OF CLOTHING FOR USE IN SEGMENTAL MODELS OF HUMAN THERMOREGULATION

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The use of segmental thermoregulation models has become more widespread in recent years, especially due to their integration into commonly available thermal modeling codes. These powerful CAE tools enable scientists to model humans within complex (i.e. asymmetric and transient) environments, for a variety of purposes (e.g. human comfort, soldier effectiveness, infrared signature, etc.). Accurate modeling of the resistance of clothing to both sensible and latent heat transfer is essential for obtaining meaningful solution results. Unfortunately, the measurement of fabric properties alone (usually using guarded hot plate devices) is not sufficient to characterize clothing thermal insulation. Proper measurement of clothing properties requires the use of thermal manikins in order to obtain the thermal and evaporative resistance of a garment as it would be worn on a human body.

In practice, thermal manikin measurements are used primarily to obtain whole body clothing properties (*Rcl*, *Re,cl* and *fcl*). Although these whole body values can be directly applied to simple (e.g., two-node) thermoregulation models, localized clothing parameters (*cl R, *e,cl R and *cl f) must be used when working with segmental models (in which body parts are treated independently).

This paper describes a technique for converting previously measured whole body clothing resistances to localized values. A more accurate method that provides segment level resistances based on the measured heat fluxes per manikin zone is also proposed.

A STUDY ON THE EFFECT OF AIR GAP ON COMFORT PROPERTIES FOR FABRIC SYSTEMS USED IN PROTECTIVE CLOTHING

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Protective clothing is designed to protect the wearers from various hazards in the environment. As clothing, these additional needs to protect against hazards pose a great challenge to maintain clothing comfort and wearability. The textile materials used in protective clothing impede body heat and moisture transfer required from the human body to maintain thermal balance. Further, the heat stress applied to the human body when wearing these protective clothing can cause serious problems to both health and safety.

An experimental and theoretical investigation of the effects of air gap on fabric thermal insulation and evaporative resistance was performed. The selected fabric systems include one layer and multilayer fabric system. Spacers with different size were used to introduce an air gap between the tested fabric system and the sweating hot plate. The experiments were conducted under both dry and wet conditions. The effects of the air gap on thermal insulation and evaporative resistance, as well as total heat loss (THL), for the selected fabric systems are identified and summarized.

In order to understand further the mechanism associated with heat and moisture transfer in the fabric system, a heat and mass transfer model was applied to evaluate the thermal and evaporative resistances of the fabric systems. The effect of air gap on both thermal and evaporative resistance with different environmental conditions was predicted and the heat transfer through the modes of conduction, convection, and radiation in fabric systems was analyzed. The model analysis shows that the contribution of the three modes of heat transfer varies with different air gap size. With larger air gap, the heat transfer by radiation increases and the conduction component decreases. This physical phenomenon indicates that improved thermal insulation of fabric systems can be achieved by modifying surface property and emissivity. Additionally, the model demonstrates that natural convection can occur in the air gap when the gap size is sufficiently large and as a result both thermal and evaporative resistances are lowered.

The results obtained from the experiments and model predictions suggest that the air gap existing between the protective clothing and human body plays a significant role in thermal and evaporative resistance provided by the clothing system. A proper fit and design of garment for different end users may provide maximum protective performance.

MOISTURE AND CLOTHING LAYERS: EFFECT OF AMBIENT TEMPERATURE ON HEAT LOSS AND INSULATION

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During the latest years the research on the effects of moisture on clothing system has been boosted. New information has revealed phenomena, e.g. "heat pipe" effect with its condensation-evaporation cycle(s) that has not been considered earlier in prediction of physiological reactions or evaluating clothing properties. Considering the material properties, e.g. the evaporative resistance measurements, the tests at homogenous conditions with registration of mass loss would be probably the correct approach. On the other hand, until there is no clear picture where condensation occurs, role of wicking and the probability of re-evaporation in multilayer clothing at different environmental conditions measuring the real heat losses in order to evaluate human thermal responses in realistic test conditions is important. An example of such need is the selection of proper means for protection against cold in prehospital care at accident sites.

In this study thermal manikin was tested with wet underwear and wrapped in 1, 2 or 7 layers of woollen rescue blankets at -15 and +10 °C. This paper discusses the issues related to possibility to improve predictions for the cases when other situations, materials or exposure temperatures are involved. A method to quantify "heat pipe" effect was proposed, and for control the calculation of dry insulation from wet tests was applied.

The measured apparent insulation, i.e. insulation based on total heat loss in wet conditions, was higher at -15 °C than at + 10 °C. That could be related to higher condensation rate in materials or suppressed evaporation. However, the measured weight loss rate (higher at -15 °C) and accumulation in layers (lower at -15 °C) did not support this conclusion. Effect could partly be related to the lower water pressure gradient between wet clothing at manikin surface and ambient air at +10 (2.5 kPa) than -15 °C (3.0 kPa).

In the case of 7 layers the highest accumulation occurred in the layers near body and in the outermost layer while only minimal accumulation of moisture was observed in the middle layers. The total accumulation was divided into ratios for each layer, and expected condensation heat to environment was based on insulation (7 layers, 1/7 of the first and 7/7 of the outer layer leaves the system). When this correction was applied to "heat pipe" effect then the corrected heat loss did lead to insulation values similar to dry tests. The method worked also for 1 and 2 layer systems with highest difference for 1 layer system. The method could be tested more accurately on a sweating cylinder/torso, where layers may be separated in order to avoid wicking or vice versa set to allow it. Using different number of layers, layer thickness and less hygroscopic materials than wool may improve estimation of the "heat pipe" effects.