Human Thermal Model Evaluation using the JSC Human Thermal Database

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Abstract

Human thermal modeling has considerable long term utility to human space flight. Such models provide a tool to predict crew survivability in support of vehicle design and to evaluate crew response in untested space environments. It is to the benefit of any such model not only to collect relevant experimental data to correlate it against, but also to maintain an experimental standard or benchmark for future development in a readily and rapidly searchable and software accessible format. The Human thermal database project is intended to do just so; to collect relevant data from literature and experimentation and to store the data in a database structure for immediate and future use as a benchmark to judge human thermal models against, in identifying model strengths and weakness, to support model development and improve correlation, and to statistically quantify a model's predictive quality.

The human thermal database developed at the Johnson Space Center (JSC) is intended to evaluate a set of widely used human thermal models. This set includes the Wissler human thermal model, a model that has been widely used to predict the human thermoregulatory response to a variety of cold and hot environments. These models are statistically compared to the current database, which contains experiments of human subjects primarily in air from a literature survey ranging between 1953 and 2004 and from a suited experiment recently performed by the authors, for a quantitative study of relative strength and predictive quality of the models.

Introduction

Scientists and engineers rely on mathematical models to describe the natural phenomena with which they deal. Mathematics affords a concise, convenient means for describing quantitatively any natural system; a means which is suitable as a tool for predicting and explaining its behavior systematically. The predictive capabilities of a mathematical model are employed to evaluate feasibility, reduce cost, improve safety, and improve function in all fields of the human endeavor toward progress.

Modeling of the human body in general, and of the human thermoregulatory system as addressed in particular here, is key to evaluating the feasibility and improving the safety of endeavors which press the envelope of the human environment. A human thermoregulatory model considers how the human body controls and maintains its

temperature, and thus its response to clothing, environment temperature, humidity, and other external factors to maintain that temperature. They are used in the design of buildings and office spaces to predict comfort [refs], in the design of flight suits for air force pilots, [refs] of protective suits for first responders such as firefighters, [refs] and environment and life support development for space exploration [refs]. These examples illustrate the range of utility for human modeling as well as the need for predicting human response to extreme environments. The alternative, human testing in conditions that could cause death or adoption of designs unsafe for human habitation, is unconscionable and extraordinarily costly.

NASA uses several models, among these the Wissler Human Thermal Model (WHTM). The WHTM was developed by Eugene H Wissler of the University of Texas at Austin to simulate the physical characteristics of the human thermal system in a transient state. This model divides the human body into 15 cylindrical elements and various subject, garment, and environment parameters are input to predict temperatures at various points of the body, sweat production and rate of evaporation, and heat exchange to the environment through conduction, radiation, and convection. The WHTM has proved a valuable tool for manned space exploration. The human thermoregulatory system is inarguably complex, however, and a mathematical model, by virtue of any faults in its interpretation of this system, can be somewhat incomplete and lacking in precision. It is to identify the weaknesses of the model in an endeavor to improve it that the tools described here were developed.

The Human Thermal Database

There is considerable value in collecting peer reviewed experimental data. When derived from literature, the data is had without the expense of performing the tests to collect it. The quantity of data available is considerable, as are the range of testing parameters. Equipment and process specific bias can be avoided through the differing apparatus each experiment might use. Further, as peer reviewed experimental data, the data is leant the weight of a community regarding its validity and methodology.

Human thermal modeling has vast long term utility to human space flight, providing a tool to predict the survivability of crew in unfamiliar space environments, so it is to the benefit of any such model not only to collect relevant data to compare it against, but also to maintain the data as a standard for future development in a readily and rapidly searchable and software accessible format. The Human thermal database is intended to do just so; to digitize the literature or format NASA test data and to store the relevant data in a database structure for immediate and future use as a standard to judge models against, in identifying model strengths and weakness, and to support model development, correlation, and evaluation.

The data structure design for this database is relational with a third normal form. The relational structure of the database is shown in Figure 1. It is composed of three major table sets, one which describes each document or project from which data is collected as seen in Figure 2, a second which describes each experiment or test and references the document table as Figure 3, and a third which contains actual data from each experiment and references the experiment table. The latter set of tables includes one that describes global parameters, seen in Figure 5, which do not change over the course of the experiment such as subject age, height, and weight. It also includes a table that contains all transient data, Figure 4, such as core and skin temperature, metabolic rate, and environment temperature. Each of these latter tables include units for time and the measured value. Additional tables include keys and descriptions for each data type in the latter two tables.

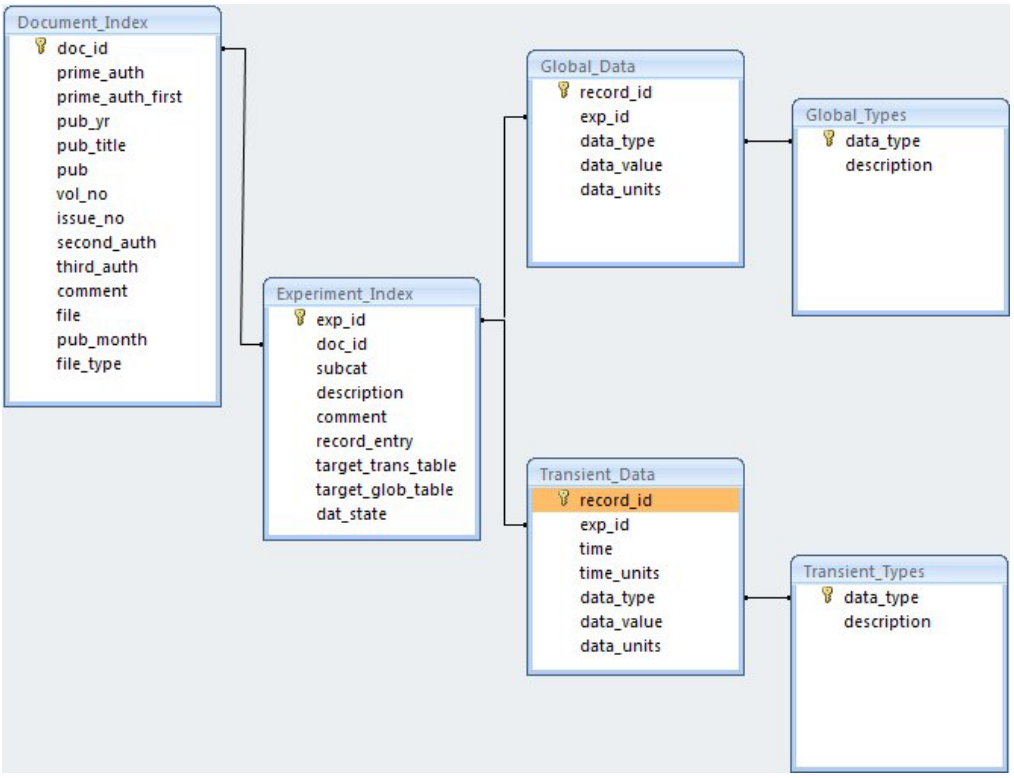


Figure 1. Human Thermal Database relational structure

doc_id	prime_...	prime_...	pub_yr	pub_title	pub	vol_no	issue_no	second...	third_a...	comment	file	pub_m...	file_t
1	Saltin	B	1968	Muscle ...	J Appli...	25	6	Gagge	Stolwijk	Note th...	BLOB (S...	12	pdf
2	Gagge	A	1969	Comfort...	Environ...		2	Stolwijk	Saltin	Similar t...	BLOB (Si...		pdf
3	Keatisu...	Waree	1996	Physiol...	Appl Hu...	15	6	Ohnaka	Tochihara	Men an...	BLOB (Si...		pdf
4	Hardy	J	1966	Partitio...	J Applie...	21	6	Stolwijk			BLOB (Si...		pdf
5	Kolka	Margaret	2001	Thermal...	U.S. Ar...			Kesick	Levine	Need to...	BLOB (Si...	9	pdf
6	Saltin	B	1970	Body te...	J Applie...	28	3	Gagge	Stolwijk	HTC off...	BLOB (Si...	3	pdf
7	Saltin	B	1972	Body te...	J Applie...	32	2	Gagge	Bergh		BLOB (Si...	5	pdf
8	Chappuis	P	1976	Heat st...	J Applie...	40	3	Pittet	Jequier		BLOB (Si...	3	pdf
9	Stolwijk	J	1966	Partitio...	J Applie...	21	3	Hardy			BLOB (Si...		pdf
10	Nielsen	M	1953	Studies ...	Acta Ph...	27	2	Pedersen			BLOB (Si...	4	pdf

Figure 2. Document table excerpt

exp_id	doc_id	subcat	description	comment	record_entry	target_trans_...	target_glob_t...	dat_state
1	1	Figure 4a	Tamb=20C, ...	Seminude, st...	6/22/2011	Transient_Data	Global_Data	Complete
2	1	Figure 4b	Tamb=20C, 7...	Seminude, sta...	6/22/2011	Transient_Data	Global_Data	Complete
3	1	Figure 5a	Tamb=10C, 7...	Seminude, sta...	6/22/2011	Transient_Data	Global_Data	Complete
4	1	Figure 5b	Tamb=20C, 7...	Seminude, sta...	6/22/2011	Transient_Data	Global_Data	Complete
5	1	Figure 5c	Tamb=30C, 7...	Seminude, sta...	6/22/2011	Transient_Data	Global_Data	Complete
6	2	Fig5a	Tamb=30, V...	n=4, Note tha...	7/27/2011	Transient_Data	Global_Data	Complete
7	2	Fig5b	Tamb=20, V...	n=4, Note tha...	7/27/2011	Transient_Data	Global_Data	Complete
8	2	Fig5c	Tamb=10, V...	n=3, DZ, RD, ...	7/27/2011	Transient_Data	Global_Data	Complete
9	2	Fig5d	Tamb=20, V...	n=4, Note tha...	7/27/2011	Transient_Data	Global_Data	Complete
10	2	Fig5e	Tamb=10, V...	n=3, DZ, RD, ...	7/27/2011	Transient_Data	Global_Data	Complete

Figure 3. Experiment table excerpt

record_id	exp_id	time	time_units	data_type	data_value	data_units
1	1	0.68768	min	Tr	37.126	C
2	1	1.4108	min	Tr	37.126	C
3	1	2.1339	min	Tr	37.127	C
4	1	2.9477	min	Tr	37.145	C
5	1	3.5801	min	Tr	37.127	C
6	1	4.4843	min	Tr	37.146	C
7	1	5.117	min	Tr	37.146	C
8	1	5.9305	min	Tr	37.146	C
9	1	6.5632	min	Tr	37.146	C
10	1	7.287	min	Tr	37.183	C

Figure 4. Transient data table excerpt

record_id	exp_id	data_type	data_value	data_units
1	1	Age	32	yr
3	1	Mass	89.5	kg
4	1	Height	187	cm
5	1	S_Area	2.18	m^2
6	1	HR_max	186	bpm
7	1	VO2_max	5.17	sLpm
8	1	Met_rest	40	kcal/m^2-hr
10	1	Env_Fluid	GAS	-
11	1	Breathing	AIR	-
12	1	Clothing	semi-nude	-
13	1	Sex	Male	-
14	1	Body_fat	12	mm_SFW
15	1	n	1	subject

Figure 5. Global data table excerpt

An emphasis on portability and embedability drove the selection of a database format to SQLite. Portability addresses platform dependence; the Wissler model was developed before the era of the desktop and of the Windows platform but it remains in use because the model is portable. The tools which are developed for human thermal modeling should similarly be sufficiently portable, having no specific hardware, operating system, or server dependence, to survive for the long term. SQLite is a public domain serverless SQL database engine, thus is platform independent in several respects. As public domain software, the source code is available should it be necessary for future portability needs. Its serverless design requires no dedicated server architecture or network hardware. The engine is designed to be cross-platform; it supports various Unix, OS/2, and Windows platforms and is portable to others. Embedability considers programmatic access to the data content and whether it can be packaged and delivered seamlessly with supporting software. SQLite uses the standard SQL database language for queries and commits. SQLite is zero-configuration, meaning no installation nor set-up procedure is required for its use. SQLite provides a C/C++ and TCL API and consequently has well supported bindings to numerous languages including Python and Fortran.

The database is populated by selected human thermal tests performed at JSC and from the literature. Among the literature data collected are those which the original Wissler code was correlated against including Saltin, Gagge, and Hardy. Conditions differ among these latter experiments, but all involve partially nude subjects in controlled environments where either a step change in environment is imposed on the subject or the subject exercises at a controlled rate. A further trove of human thermal data performed under a wide array of conditions was collected through a literature survey. Significant findings containing relevant data from the literature review are shown in Table 1. This survey of datasets affords thus the opportunity to assemble parameters sufficient to statistically and quantitatively evaluate predictive human thermal models.

Table 1. Significant Literature Findings

Primary Author		Year	Study Title
Nielsen,	M	1953	Studies on the Heat Loss by Radiation and Convection from the Clothed Human Body
Hardy,	J	1966	Partitional calorimetric studies of man during exposures to thermal transients
Stolwijk,	J	1966	Partitional calorimetric studies of responses of man to thermal transients
Saltin,	B	1968	Muscle temperature during submaximal exercise in man
Gagge,	A	1969	Comfort and Thermal Sensations and Associated Physiological Responses during exercise at Various Ambient Temperatures
Saltin,	B	1970	Body temperatures and sweating during thermal transients caused by exercise
Saltin,	B	1972	Body temperatures and sweating during exhaustive exercise
Givoni,	B	1972	Predicting rectal temperature response to work, environment, and clothing
Gagge,	A	1973	Physiological Bases of Warm Discomfort for Sedentary Man
Olesen,	B	1973	The Skin Temperature Distribution for Resting Man in Comfort
Gonzalez,	R	1974	Heat acclimation and decline in sweating during humidity transients
Chappuis,	P	1976	Heat storage regulation in exercise during thermal transients
Kobayashi,	K	1980	Thermoregulation during rest and exercise in different postures in a hot humid environment
Drew,	A	1992	Effectiveness of NASA 1032 & 1035 and Air Force 1030 & 1034 Suits in Protection Against Cold Water Hypothermia
Keatisuwan,	W	1996	Physiological Responses of Men and Women during Exercise in Hot Environments with equivalent WBGT
Kolka,	M	2001	Thermal Comfort and Thermal Sensation During Exposure to Hot, Hot-Humid and Thermoneutral Environments
Nyberg,	K	2001	Model of Human/Liquid Cooling Garment Interaction for Space Suit Automatic Thermal Control
Richards,	M	2004	Modeling fire-fighter responses to exercise and asymmetric infrared radiation using a dynamic multi-mode model of human physiology and results from the Sweating Agile thermal Manikin

The Human Thermal Database Tool and Utility Framework

A software tool and utility framework has been developed using Python in conjunction with the human thermal database. This software is intended to facilitate and automate the use of the database. The Python language is chosen for its platform portability, integral support for SQLite, math and science modules, and interoperability modules for C/C++ and Fortran. The software provides a framework to standardize data from disparate data sources, to format this as input to run various human thermal models, and to support the statistical and quantitative analysis of human thermal data. Thus, this framework supports the evaluation of human thermal models relative to experimental data and is a useful tool to support accelerated development of human

thermal models. The software structure is class-based in order to provide a modular framework that is flexible enough to incorporate the diversity of human thermal model software used by NASA. This is an important design consideration as the utility of the database transcends the Wissler software that is presently supported by this framework.

A correlation tool created using this framework determines a set of statistics evaluating the goodness of fit of the Wissler model with respect to experimental data. The tool determines regression statistics, including standard deviation and residuals, of each experiment by treating the model as a regression function. The tool also performs the Kolmogorov-Smirnov 2 sample test (KS2T) comparing the experiment and model data. KS2T is a non-parametric statistical test which determines the probability that two given samples come from the same distribution, and thus, is performed to gauge how well the two data sets match.

The tool is quick, repeatable, and consistent, making the statistics produced useful in code maintenance by providing quantitative 'scores' by which to judge the benefit from algorithm modification or correlation of the code. One could, for example, make changes in the model to address an apparent instability then run the auto-compare tool to identify how the quantitative score has changed relative to a score taken prior to changes.

Further, using the parameters of the experiments maintained in the database, this tool allows a regression study revealing the relative strengths and weaknesses of the Wissler model. For example, a linear regression of the statistic for all dataset might indicate that a model is poor for one sex or that its predictions are insensitive it subject age.

Results and Discussion

The Wissler model is compared to experimental data using the

Figure 6 shows a comparison of subject core temperature predicted by the Wissler model to the same from experimental data published by Gagge et. al. The experimental data shown is the average of 4 subjects. Each subject exercises on a stationary bike at approximately 70% of that individual's maximal oxygen uptake in a room having an ambient temperature of 30C and relative humidity of ~40%. Figure 6 contains two plots, a) which shows a side-by-side comparison of the experimental and model data, and b) which shows the residuals, or the difference, between the two elements of the comparison. The Wissler model correlates very well to this experiment following an initial period of approximately 5 minutes where the model predicts considerably lower than the experimental data. It matches the trend and magnitude of the experiment to within 0.1C, as shown by the residuals, for an overall standard deviation of 0.08C and a Kolmogorov-Smirnov (K-S) statistic of 0.10, both quantitative

indicators of an excellent fit between the model and experiment. The predicted dip in core temperature during the first 5 minutes appears in many Wissler predictions at the onset of exercise. It is believed that this deviation may be an artifact of the Wissler sweat or extremities blood vessel dilation algorithms.

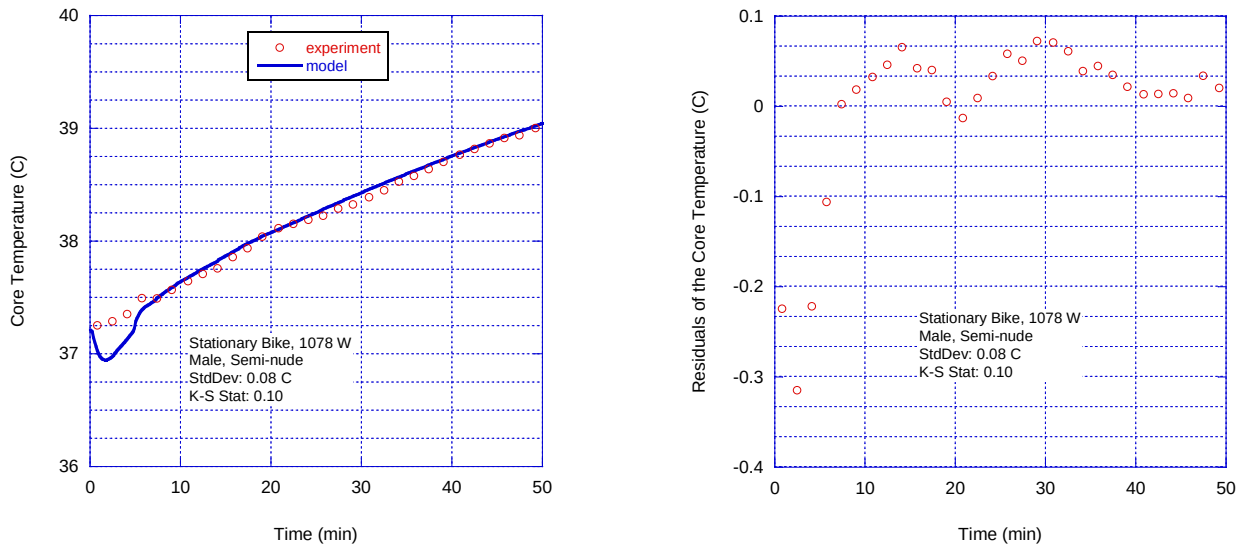


Figure 6 – a) Core temperature and b) residuals of experiment vs. Wissler model data for a semi-nude subject exercising on a stationary bike at 1078 W. [Gagge]

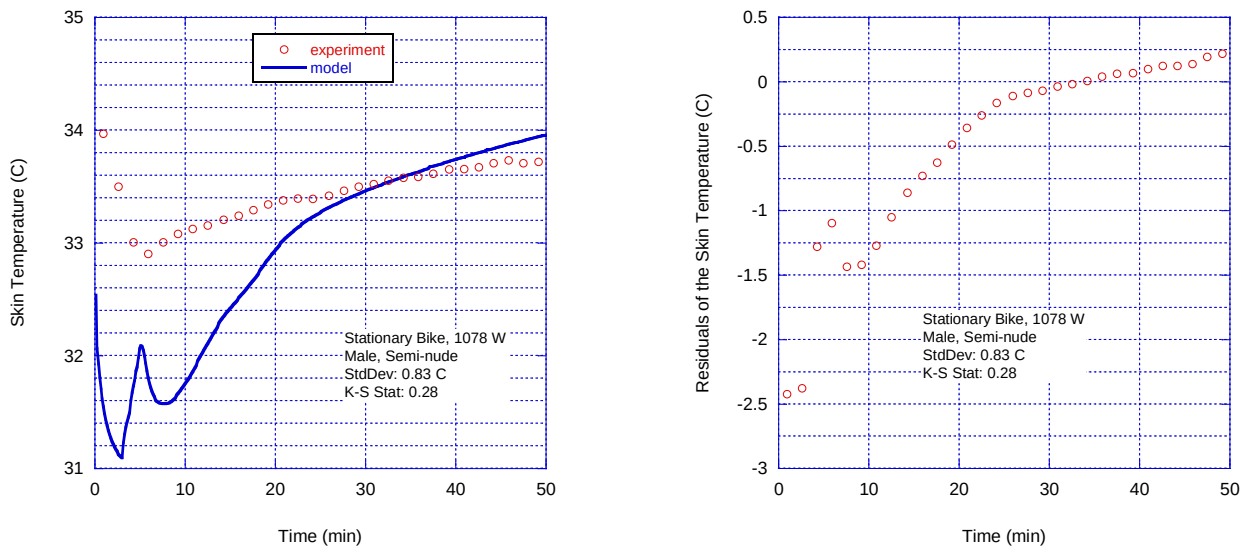


Figure 7 – a) Skin temperature and b) residuals of experiment vs. Wissler model data for a semi-nude subject exercising on a stationary bike at 1078 W [Gagge]

Figure 7 shows a comparison of subject skin temperature for the same experiment as above. Predicted skin temperature does not match experiment quite as well as core temperature, but this should be expected. The published skin temperatures of this

experiment, in fact, vary considerably by subject. Standard deviation for the skin temperature comparison is 0.83C, and K-S statistic 0.28. The range of skin temperature for the subjects from the experiment varies by as much as 2C, though. Interestingly, the artifact that appears in core temperature over the first five minutes also seems to appear here.

Figure 8 shows a comparison of subject core temperature for a two-step experiment in which test subjects initially exercise on a stationary bike at 25% maximal oxygen uptake for 30 min followed by exercise at 50% maximal oxygen uptake for a final 30 min. Experimental results are published by Saltin et. al. and reflect a single subject exercising in a room with an ambient temperature of 20C and relative humidity of 40%. As this is a comparison against a single subject, the comparison is subject to the variation inherent of human physiology. Nevertheless, the comparison here indicates similar trends between the experiment and predicted core temperature, though the model under predicts core temperature throughout the experiment by as much as 0.5C. Standard deviation between model and experiment is 0.35C, and the K-S statistic 0.38. The deviation noted in the previous experiment is apparent here too.

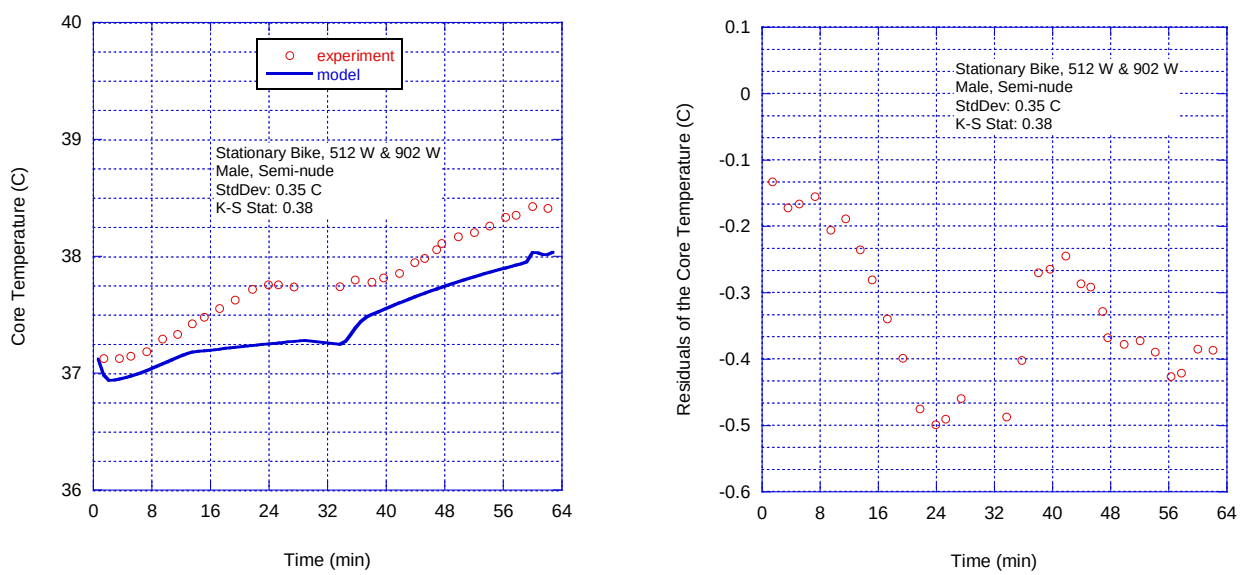


Figure 8 – a) Core temperature and b) residuals of experiment vs. Wissler model for a semi-nude subject exercising on a stationary bike at 512 W then at 902 W [Saltin]

Figure 9 shows subject skin temperature for the same experiment described in Figure 8. The predicted trend again reasonably matches but under predicts the experiment. The initial drop noted in the above comparisons is present and exaggerated in this skin temperature prediction. In fact, this deviation approaches 4C from experiment at its worst, though standard deviation of the model from experiment is 1.79C and K-S statistic is 0.63.

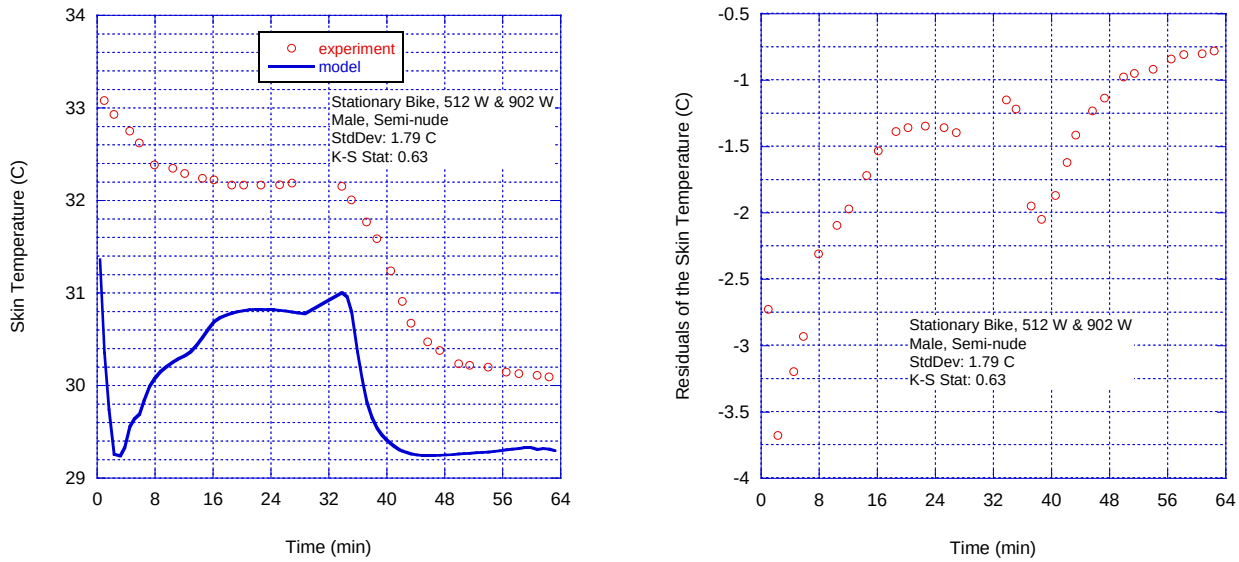
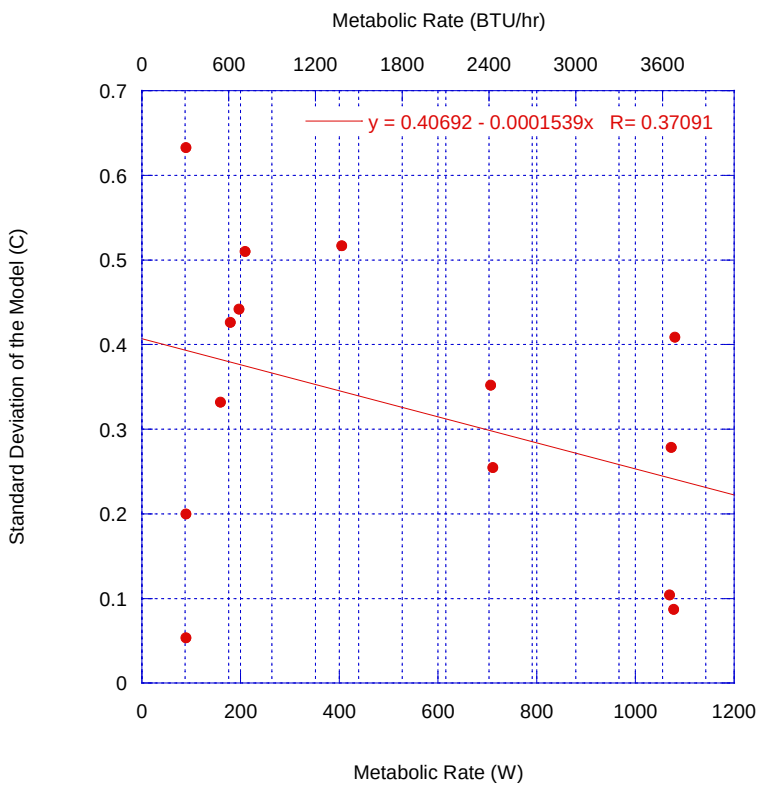
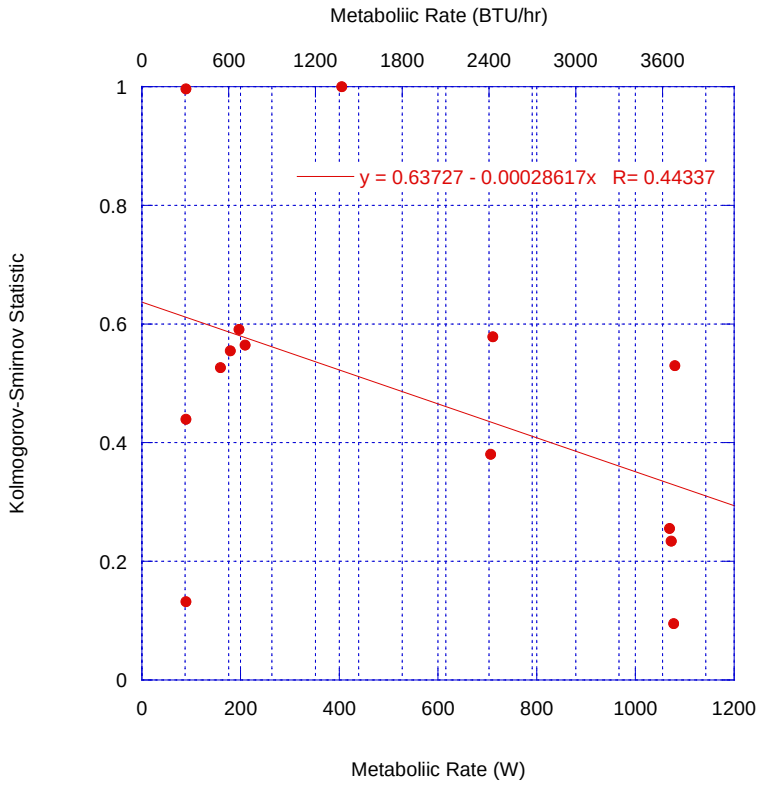
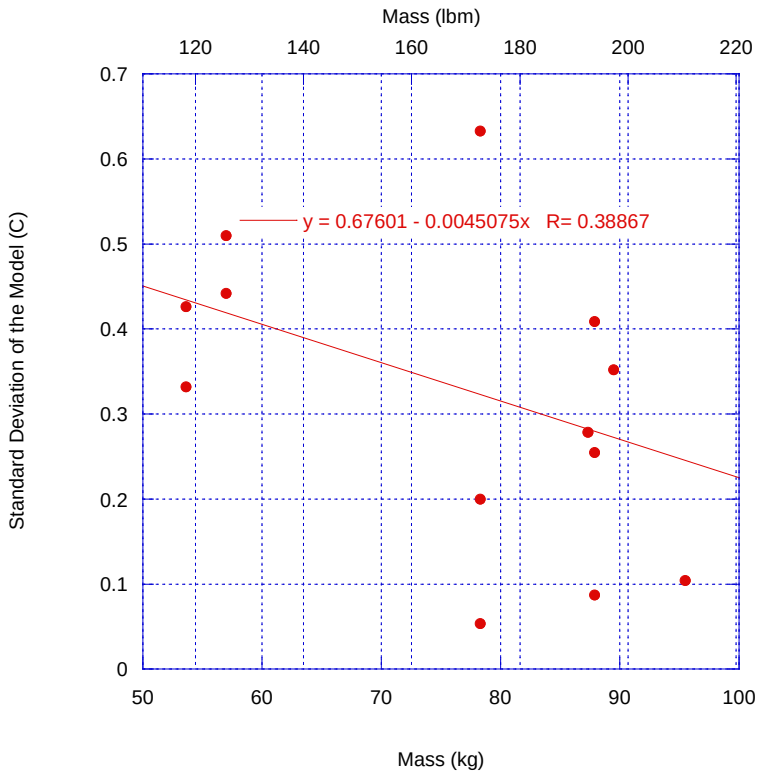
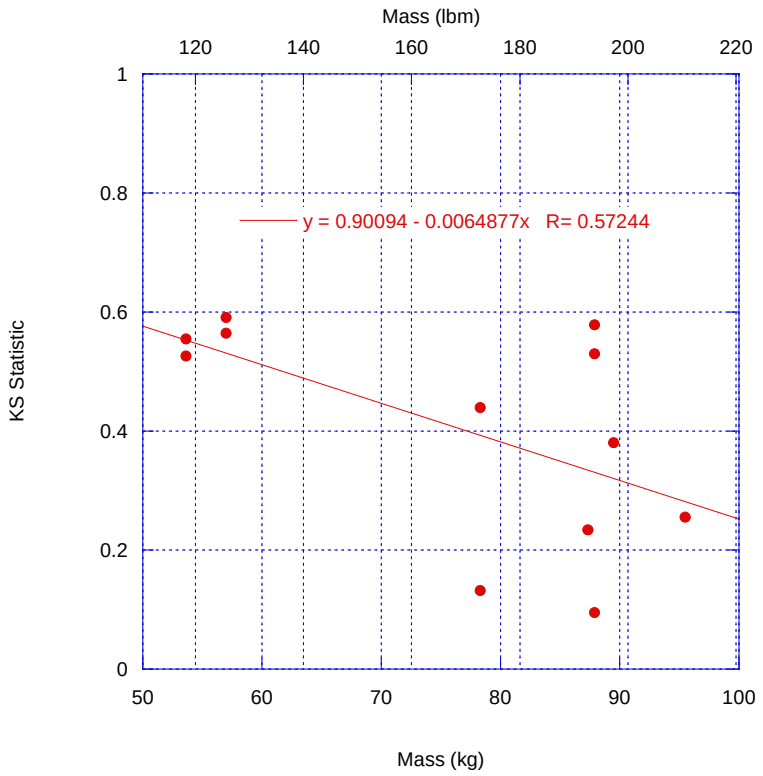


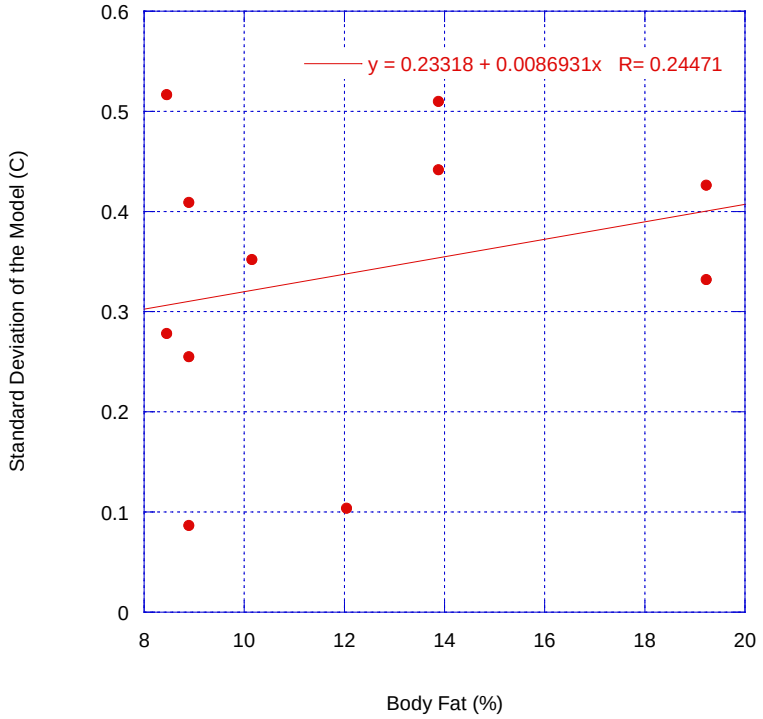
Figure 9 – a) Skin temperature and b) residuals of experiment vs. Wissler model for a semi-nude subject exercising on a stationary bike at 512 W then at 902 W [Saltin]

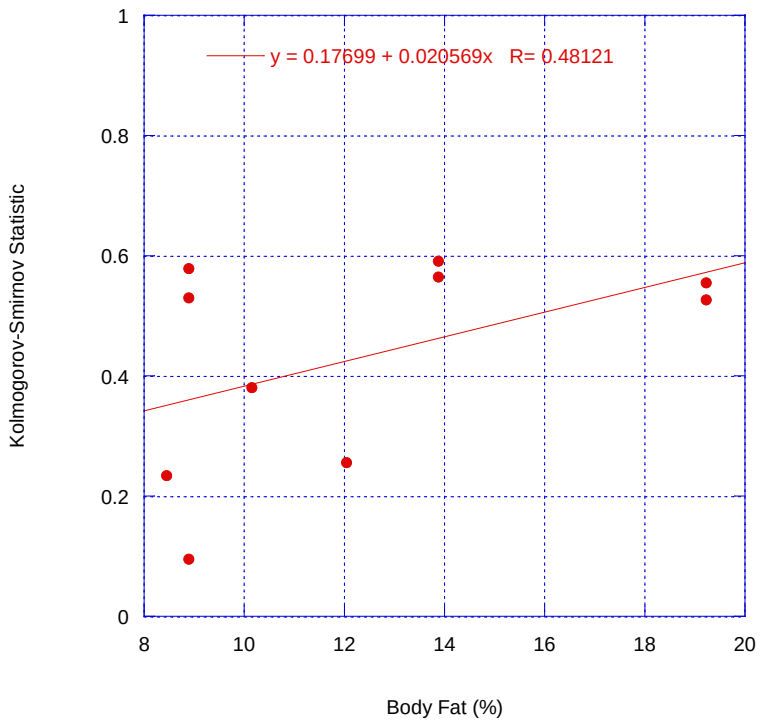



Metaboliic Rate (BTU/hr)
0
600
1200
1800
2400
3000
3600
1
0.8
0.6
0.4
0.2
0
y = 0.63727 - 0.00028617x R= 0.44337
Kolmogorov-Smirnov Statistic
0
200
400
600
800
1000
1200
Metaboliic Rate (W)


Mass (lbm)
120
140
160
180
200
220
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
y = 0.67601 - 0.0045075x R= 0.38867
Standard Deviation of the Model (C)
50
60
70
80
90
100
Mass (kg)


Mass (lbm)
120
140
160
180
200
220
1
0.8
0.6
0.4
0.2
0
KS Statistic
y = 0.90094 - 0.0064877x R= 0.57244
50
60
70
80
90
100
Mass (kg)


0.6
0.5
0.4
0.3
0.2
0.1
0
Standard Deviation of the Model (C)
y = 0.23318 + 0.0086931x R= 0.24471
8
10
12
14
16
18
20
Body Fat (%)


y = 0.17699 + 0.020569x R= 0.48121
Kolmogorov-Smirnov Statistic
Body Fat (%)
0
0.2
0.4
0.6
0.8
1
8
10
12
14
16
18
20