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SOFTWARE METAPAPER

Comfort Simulator: A Software Tool to Model Thermoregulation and Perception of Comfort

Jagir R. Hussan and Peter J. Hunter
Auckland Bioengineering Institute, University of Auckland, NZ
Corresponding author: Jagir R. Hussan (r.jagir@auckland.ac.nz)

Thermophsyiological comfort is critical to well-being and optimal productivity of humans. Environmental changes, modern materials and novel occupational settings necessitate evaluation of their impact on comfort and inform both product design and occupational health. We present an open-source research software tool to simulate thermophysiological comfort for different human geometries, body-constitution conditions, clothing, ambient temperature, humidity and radiative heat flux conditions. The tool, developed using python, integrates a diverse set of models. The components that code the models can be easily replaced and the simulation pipeline can be executed with minimal disruption.

Keywords: Thermophysiological comfort; Thermoregulation; Numerical Simulation; Heat and Mass Transfer; Product design
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(1) Overview

Introduction

Climate change is a significant challenge facing humans. On the one hand we need to address the issues that are exacerbating the warming process, and on the other we need to develop lifestyle related products that would help mitigate the effects. Thermophysiological comfort [1, 4] is critical to human performance and is significantly affected by the warming planet. New materials for housing, clothing and protection from harsh elements are being developed. However, significant costs associated with the industrial design and development process stifle equitable development i.e. not all communities have access or are able to afford these technologies, even though the effects of climate change are universal.

Computer simulations may help in reducing these costs and in identifying material suitable for specific applications, and population specific requirements. Development of mathematical models to characterise comfort, the interaction between humans and materials have been an active area of research. Consequently, there are several models [2, 6, 15, 16] in published literature addressing various aspects of thermophysiological comfort.

Thermoregulation models can be broadly classified into two categories: those that are empirical [5] and those that are physiologically informed [9, 11, 14, 17]. Empirical models assume physiological conditions and local effects do not have much impact on whole body thermal sensation and comfort. However, whole body thermal comfort depends on the thermal sensations of local body parts [19]. In experiments, the skin and core temperatures of subjects are used to characterise thermal sensation and comfort. Local effects are accentuated in non-uniform and/or transient environments and empirical models are not suitable. Such situations require a dynamic thermoregulation model to simulate the skin and core temperature. Further, the model should take into account the individual body characteristics that influence the thermal state of the body.

ThermoSEM [11] is a commercial software that has been used to perform such simulations. There are tools like the CBE Thermal Comfort Tool [8] that are freely available, however, it uses an empirical model for predicting comfort. To the best of our knowledge there isn't an open-source software tool that 1) integrates relevant models to predict local skin and core temperatures, 2) enable the study of comfort under various environmental, clothing and radiative heat flux exposure conditions, 3) for realistic human geometries and body constitution. We believe this gap limits the potential for exploring and developing novel solutions, especially it restricts disadvantaged communities, domain experts and designers who do not have access to such commercial software or have the technical know-how to develop the models into useful software.

Our aim is to develop an open-source software tool that would enable experts and non experts alike to perform such simulations. Additionally, the software should be modular such that modules that are used to generate the target human geometries, simulate thermoregulation, and to predict comfort metrics can be easily replaced or modified without affecting the simulation pipeline. *Auckland Bioengineering Institute*'s Comfort Simulator is a user friendly, free, open-source tool that enables the simulation of thermoregulation on realistic human geometries for various ambient, body-constitution and metabolic activity levels. **Figure 1** shows a schematic representation of the developed simulation pipeline.

Implementation and architecture

In line with modular approaches that enable independent development of the modules by varied experts, and to enable the use of need based usage of compute-infrastructures; a three layered software architecture was designed, **Figure 2**.

The presentation layer provides the necessary GUI's for setting up a thermoregulation experiment. The layer also provides a viewer through which the status of ongoing simulations can be queried, and results from completed simulations can be visualised and analysed. The business layer contains the logic to setup the simulation based on the inputs from the user. The logic also computes the model parameters suitable for the anatomy and body composition specified by the user. The reference parameters and anatomical models are served through a Data layer. The presentation and business logic layers compose the client; and are together responsible for creating a description that completely defines the experiment, and the parameters necessary for the thermoregulation model to simulate the experiment.

The compute layer can be deployed on the same machine as the client or on a remote machine and defines the server component. It primarily concerns with the simulation of a thermoregulation experiment as described by the client's business logic. It also provides some housekeeping services such as reporting on ongoing simulations, storing results of completed simulations. It uses a filesystem based datalayer for these housekeeping services. All messages between the layers are encoded in JSON and are in human readable format.

Key modules and their implementation in the current release are discussed below.

Thermophysiological Model

The software implements the 65MN thermoregulation model [16]. The 65MN model divides the body into sixteen segments, each segment is further divided into four layers characterising the skin, fat, muscle and core layers. Thermoregulation is then modelled as function of internal body heat production, heat transmission across these four layers, sixteen body segments and blood, generating 65 degrees of freedom. Heat generation within the muscle, heat loss due to respiration and sweating are orchestrated by a control system that approximately models the hypothalamic control of body temperature.

The model requires each body segment's surface area, heat conduction, storage, and radiation coefficients as

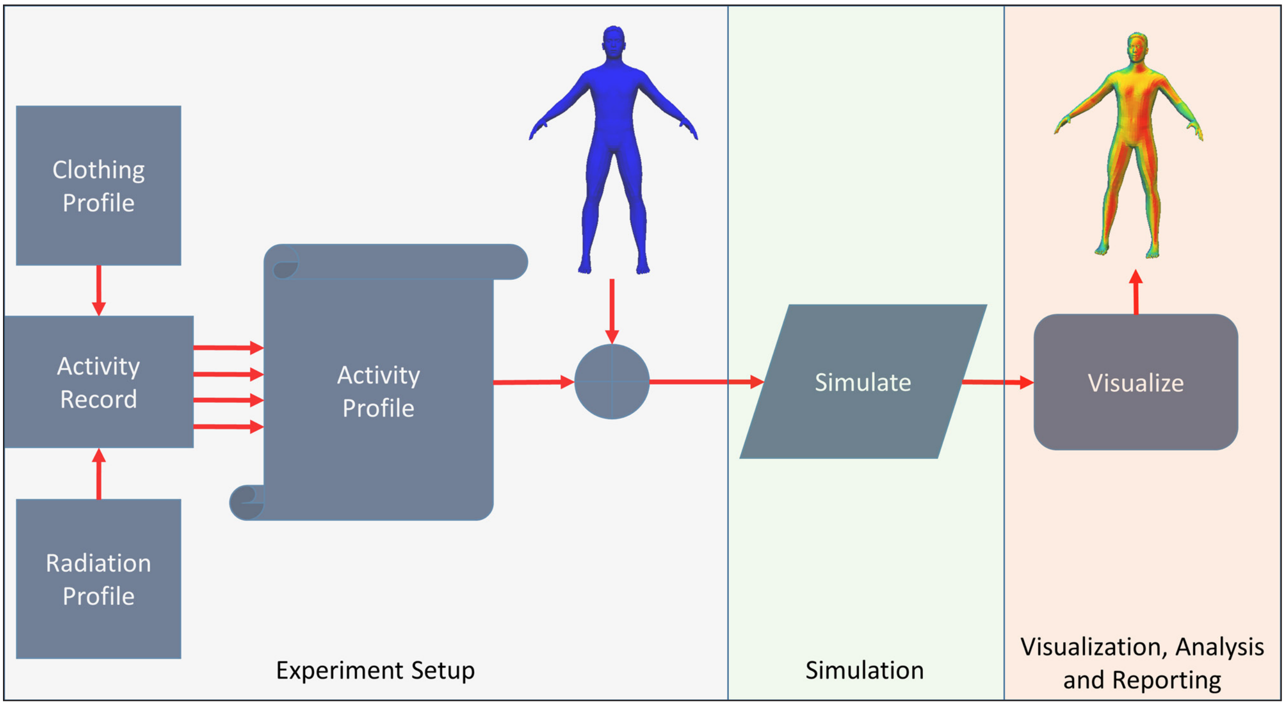

Figure 1: Schematic representation of the simulation pipeline. Users setup the experiment by defining the target individuals activity profile and the geometry, the model can then be numerically simulated and the results can be analysed and visualised. The UI provides features to generate reports and render results on the geometry. For instance, a individual whose geometry is defined by a 3D mesh (blue mesh) when subject to an activity described in the activity records ends up having a non uniform body temperature distribution, which can be computed and visualised on the 3D mesh (hot map mesh).

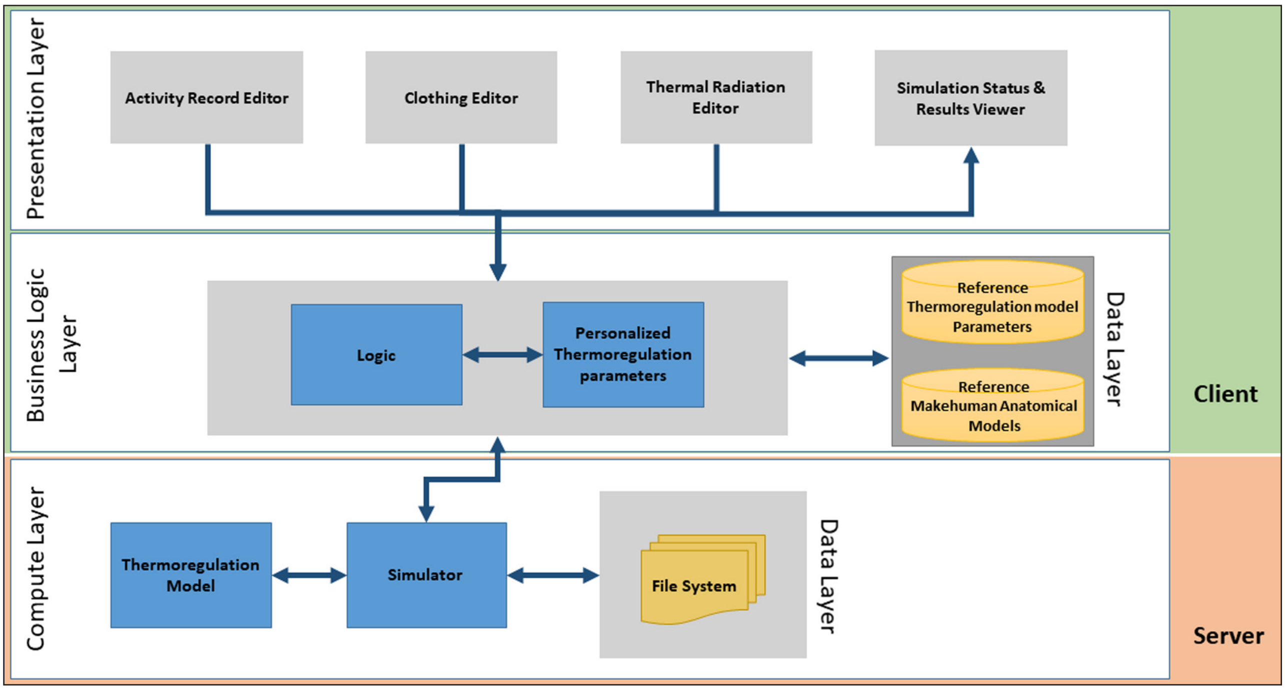

Figure 2: High level software architecture of the comfort simulator.

parameters. Specification of sources/sinks of heat are also required. Sources include the heat produced within the body, characterised by the metabolic activity level (*met*). Other sources/sinks include the ambient heat and moisture characterised by the ambient temperature, relative humidity, and radiative heat flux. The effect of these sources/sinks is modified by the velocity of surrounding air. Heat and moisture exchange with the environment is modulated by clothing. Fabric's thermal behaviour is often characterised using the steady state heat and vapour resistance. Simulating the model to predict the body's thermal profile and perceived comfort requires specification of the above parameters, internal state and environmental conditions.

The current implementation assumes the body-constitution parameters remain invariant over the time of interest and are specified only once when the human geometry is setup. However, metabolic activity level, ambient conditions and clothing are allowed to change. A description of these along with the duration for which they are active will hence forth be referred to as an *activity record*. An individual's lifestyle or snapshot of their daily activity can be described by a sequence of activity records. This sequence of records is called as the *activity profile*. Regression based empirical models of Zhang [18] and Fanger [5] are then used to determine the comfort level of the individual based on the regional temperature profile.

Modelling based on realistic human geometries

The 65MN model representation is not geometrically realistic. Further, the model parameters should reflect gender, age and body-constitution of the target human. The work of Ozeki et al. [12], demonstrates how to adapt the 65MN model to simulate a full scale human model by appropriately personalising the parameters. The process generates a $4 \times n + 1$ dimensional model, where n is the number of surface-faces of the mesh. The parameters can be personalised to a target individual based on the individual's age, height, weight and cardiovascular fitness to closely represent the inter-layer, inter-segment heat transfer, and the muscle heat generation characteristics that may be observed in that individual. Using this, a realistic model can be solved to determine the temperature profile for a activity profile.

Generating representative geometries

Generating meshes that are representative of a target individual is a complex process. For population specific thermoregulation studies, it may be appropriate to use meshes that are representative but not exact. To this end, we leverage the makehuman project [3] to generate representative human meshes. Briefly, the project provides an open-source, freely available tool to create meshes that characterise a human of specific age, gender, race, and body-constitution.

Decoupled simulation layer

The client-server based architecture allows users to handle long, computationally expensive simulations. The simulation module can be setup as a service, and the user can seamlessly submit experiment setups for simulation via the client. Progress information and results can also be visualised using the client. Of course, if one is using a powerful workstation to perform the simulation, the client itself can simulate and render the results as simulation progresses.

The tool and the code are distributed with a User manual, that outlines the steps for creating meshes, activity profiles, clothing profiles, radiation profiles, initiating simulations and visualising results.

Quality control

We performed functional testing of the simulation pipeline to compare simulated skin temperatures with physiological studies reported in published literature. We used experimental data published by Hardy and Stolwijk for three male subjects exposed to a step change from 43°C at 30% RH to 17°C at 40% RH. Age, Height and Weight characteristics of these subjects are listed in **Table 1**. The human subjects walked quickly from one chamber to another which took less than 1 min. The rectal and the average of 10 areas of skin temperatures as well as evaporative heat loss are presented in [7]. They performed similar tests using an upward step change from 30°C at 40% RH to 48°C at 30% RH. The rectal and the average of 10 locations of skin temperatures are presented in [13].

Activity records for both the above experiments were created using the Activity Designer UI provided by the software tool. A step change in temperature and humidity was introduced and the transient conditions experienced by the test subjects while moving from one chamber to another were ignored as they moved across in less than a minute.

The subjects were assumed to be nude and a nude clothing model was created using Clothing designer (provided by the software tool). The speed of ambient air was set to 0.0 m/s (experimental setup reported 0-10 cm/s) for all body segments. The resulting skin resistances were automatically calculated by the clothing designer.

The studies [13] and [7] reported the average temperature profiles for the three male subjects. To model this, geometries of three Caucasian males of good health with Age, Height and Weight characteristics in **Table 1** were created using makehuman tool. Activity record for each experiment along with the male geometry mesh was loaded. The age, height and weight properties corresponding to a subject was specified when the mesh was loaded. The experiment was then simulated and the rectal temperature and mean skin temperatures were plotted. These temperatures were then output as csv files from the graphs context menu. The above steps were repeated for each subject for each experimental setup.

The associated activity records, clothing definition, and geometric mesh are provided with the software code. Users and developers can easily reuse these records to perform the test.

Table 1: Characteristics of subjects used in experimental studies. Reproduced from [13].

	Age, years	Height, cm	Weight, kg
1	25	195	88.6
2	22	184	76.1
3	23	175	110.0

Comparison with experimental results

Once the data for these experiments were obtained. The average rectal and mean-skin temperatures for each experimental setup were computed and plotted against the experimental data. These results are presented in **Figure 3**. The Tanabe 65MN thremoregulation model, currently implemented in the software tool, assumes that any node of a body segment receives blood at the same temperature as the core. This is not valid during large transitions in ambient conditions. For instance, the arterial blood temperature decreases because of countercurrent heat exchange and lowers the temperature of extremity. This assumption also impacts the core temperature during such transitions. This explains the difference observed during transitions away from steady state. Despite this, the model does closely predict the skin temperatures and the transitions. The Tanabe 65MN model can be improved/extended further as discussed in [10]. Addition of such extensions to the software is a subject of ongoing work.

(2) Availability

Operating system

The software has been implemented in python 3, it runs on any operating system that runs python 3. As of 2019, the publicly released OpenCMISS-ZINC binaries for Windows OS only support python 3.6 bindings. Future binaries releases will support python 3.7 bindings. The software code is independent of this and will work for all python 3 versions, as it already does for other OS's.

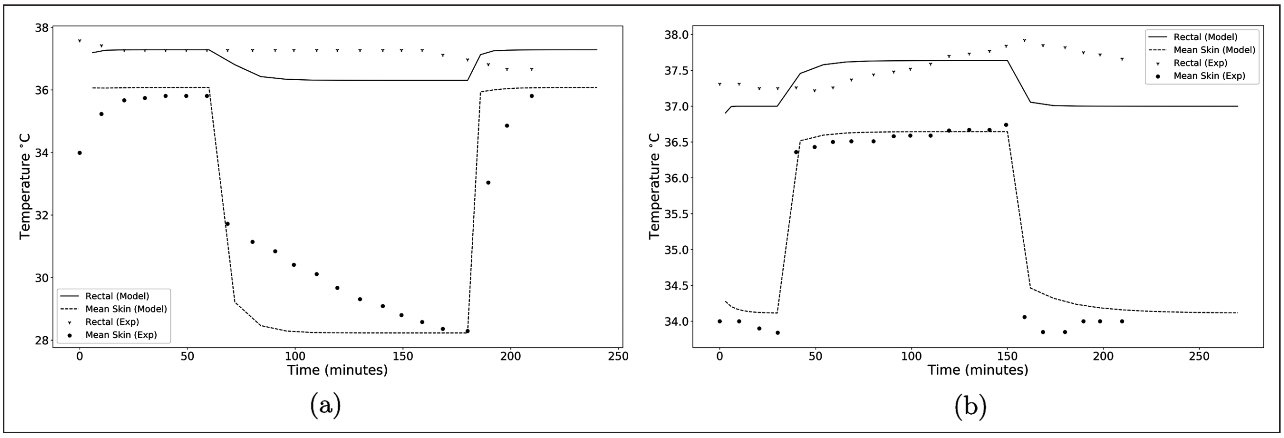

Figure 3: Comparison of measured [13] and simulated temperatures **(a)** skin and rectal temperatures during cold step-change from 43C, 30% RH to 17C, 40%RH; **(b)** skin and core temperatures during hot step-change from 30C, 40% RH to 48C, 30% RH.

Programming language
Python 3.

Additional system requirements
None

Dependencies
PyQt5, ZeroMQ, OpenCMISS-ZINC

List of contributors
Jagir R. Hussan, lead designer and developer. Dr. Richard Christie, OpenCMISS-ZINC lead designer. Mr. Alan Wu, and Mr Hugh Sorby, OpenCMISS-ZINC developers.

Software location
Archive
Name: Github (master).
Persistent identifier: https://github.com/ABI-Software/abics
Licence: Apache License 2.0
Publisher: Jagir R. Hussan
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Code repository
Name: Github (develop).
Persistent identifier: https://github.com/ABI-Software/abics
Licence: Apache License 2.0
Publisher: Jagir R. Hussan
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Language
English

(3) Reuse potential

There are many models of thermoregulation in published literature and few online tools to evaluate comfort. The software tool integrates essential models and provides a user friendly interface to perform simulations. The tool enables simulation of thermal profiles on realistic human geometries. The tool can also predict the comfort ratings that can be expected for a given activity profile. This eliminates the hurdle of implementing these models in computer code for domain experts who would rather focus on aspects that relate to say clothing design, interior design or various aspects of thermoregulation modelling. The tool does not require specialised hardware or software and can be executed on widely available computing devices. The models in the simulation pipeline are loosely coupled with the explicit aim of enabling the community to develop and share other models/implementations.

The software tool is aimed at enabling researchers, and domain experts who may otherwise not be able to explore such solutions due to the lack of free and open-source software that integrates a multitude of models necessary for simulating the problem. The tool is modular and has been developed using python with the explicit aim of encouraging users without a strong background in computer programming to modify the software. It has a low development overhead and can be modified with freely available quality software development tools. As an open-source project, users are encouraged to provide feedback, share code, models and contribute to improving the software.

Contact and support
The Github repository acts as a central communication platform for questions, suggestions, bug reports, and user contributions. Additionally, the corresponding author can be contacted via e-mail for support.

Competing Interests
The authors have no competing interests to declare.

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