Warfighter Physiological Status Prediction

Zhiqing Cheng	Jingwen Hu	James Yang	Diana Sanford, Reed Hoyt, and Gary Zientara
Innovision, LLC.	**University of Michigan**	**Texas Tech University**	**US Army Research Institute of Environmental Medicine**
Dayton, OH	**Ann Arbor, MI**	**Lubbock, TX**	**Natick, MA**
zcheng@innovisionllc.com	jwhu@umich.edu	james.yang@ttu.edu	{diana.p.sanford.ctr, reed.w.hoyt.civ, gary.p.zientara.civ}@mail.mil

ABSTRACT

Dismounted warfighters often experience physiological strain close to their physiological limits in their missions, such as patrolling in a desert in high temperatures or venturing through high mountain terrain with a restricted oxygen supply. The physiological strain experienced by a warfighter not only affects his performance but also may lead to injury or even death. Therefore, in this paper, investigations were performed to develop a systematic procedure for predicting an individual warfighter's physiological status, which includes (a) Environment set-up, to identify a geolocation and to determine environmental conditions for a mission; (b) Warfighter modeling and simulation, to create a digital human model for a warfighter and to replicate his mission activities by animating the model using motion capture data; (c) Physical activity energy expenditure analysis, to calculate the metabolic energy required for a warfighter to undertake his mission tasks based on the inverse kinematics and inverse dynamics of his body motion; and (d) Physiological status prediction: to predict the status for an individual warfighter based on his personal physical/physiological characteristics, environmental conditions, and activity intensity represented by the rate of metabolic energy required. A software system was developed to implement the procedure and to provide basic capabilities for the prediction. A case study was performed to test and demonstrate the functions of the software system.

ABOUT THE AUTHORS

Dr. Zhiqing Cheng is the founder and CEO of Innovision, LLC., a start-up and fast-growing company focusing on developing technologies related to digital humans and using these technologies for human-centered products and services. He has vast research experience in the areas of digital human modeling and simulation, artificial intelligence and machine learning, computer vision, and structural vibration. He has assumed many R&D projects as the principal investigator and published over 100 technical papers as the lead author.

Dr. Jingwen Hu earned a PhD in biomedical engineering from Wayne State University and an MS and a BS in automotive engineering from Tsinghua University. He has been working at the University of Michigan Transportation Research Institute (UMTRI) for the past ten years, most recently as a Research Associate Professor. His research interests primarily focus on impact/injury biomechanics in motor-vehicle crashes by a multidisciplinary approach using a combination of experimental, computational, and epidemiological procedures.

James Yang received the B.S. and M.S. degrees in automotive engineering from Jilin University, China, in 1989 and 1992, respectively. He received a Ph.D. degree in mechanical engineering from the University of Iowa, USA, in 2003. He is currently a professor with the Department of Mechanical Engineering, Texas Tech University (TTU), Lubbock, Texas, USA. His research interests include digital human modeling and simulation, bio-inspired systems, biomechanics, healthcare engineering, and robotic and mechanical systems.

Dr. Diana Sanford received her BS in Chemistry from Stockton University in 2011 and her PhD in Computational Chemistry from Tufts University in 2017. She was a Postdoctoral Scholar at Tufts University from 2017–2018 before joining USARIEM in 2018, where she is currently a Postdoctoral Fellow in the Biophysics and Biomedical Modeling Division, specializing in simulation and high-performance computing.

Dr. Reed Hoyt received his BS in Biology from the University of Arizona in 1973, and his PhD in Biomedical Sciences with a specialization in Physiology from the University of New Mexico in 1981. He was a Post-Doctoral Fellow (1981–1984) and then Research Assistant Professor at the University of Pennsylvania, Philadelphia, PA (1984–1986), before joining USARIEM in 1986 where he served as Chief of the Biophysics and Biomedical Modeling Division and is now a Senior Physiologist.

Dr. Gary Zientara received his BS with Honors in Chemistry (Magna Cum Laude) from Syracuse University in 1974 and PhD in Physical Chemistry from Cornell University in 1979. He was a Research Scientist at Massachusetts Institute of Technology, 1982–1993, and then at Harvard Medical School and Brigham and Women's Hospital Boston, MA from 1993–2014, and as Associate Professor of Radiology, 2003-2014. Since 2014 he is a Senior Research Scientist at USARIEM in the Biophysics and Biomedical Modeling Division.

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zcheng@innovisionllc.com	jwhu@umich.edu	james.yang@ttu.edu	{diana.p.sanford.ctr, reed.w.hoyt.civ, gary.p.zientara.civ}@mail.mil

INTRODUCTION

Dismounted warfighters often experience physiological strain close to their physiological limits in their missions. For example, marines during hot weather patrols in Iraq are close to their physiological limits. Operations in Afghanistan, where heavy combat loads, semi-encapsulating clothing and armor, rugged terrain, restricted oxygen availability, and thermal extremes are common, are also likely to push warfighters to their limits [1]. Human physiological status refers to the state of the body or bodily functions, such as blood pressure, breathing rate, pulse rate, and body temperature. Physiological status provides the information and indication about an individual's health and physiological performance. With the advent of personalized protective equipment and performance enhancement devices for warfighters, predicting and analyzing physiological status and performance of an individual warfighter under various mission conditions becomes necessary and important.

Previously, predicting soldier work-rest cycles and training limits could only be addressed using generalized models based on the estimated inputs about individuals and ambient conditions [2, 3], provably due to lack of physical and physiological modeling of individual warfighters. Now by using the Individualized Avatar with Complete Anatomy (IAVCA) [4], building an individualized model for a warfighter becomes feasible and affordable. An IAVCA model is constructed by using affine transformation of a standard anatomy finite element (FE) mesh (consisting of irregular tetrahedral elements) to fit within the 3-D body surface scan mesh of the individual. The model provides a sound approximation of individual anatomy while retaining an accurate description of the body shape. An IAVCA can be deformed to any desired pose through a software tool—DACAA (Dynamic Avatars with Complete Articulated Anatomy) [5], providing medically correct description of human body in various poses and movements. With these unique features, the IAVCA can be used for Individual Warfighter Physiological Status Prediction (IWPSP).

The objective of IWPSP is to analyze and predict the physiological strain experienced by a dismounted warfighter during Live, Constructive, and Virtual (LVC) training and in-theater missions, which include thermal-work strain limits, impending musculoskeletal injury and physical fatigue limits, pulmonary exposures limiting performance, and specialized environmental exposures (e.g., hypoxia, peripheral cold monitoring). Therefore, IWPSP can be used for mission planning and rehearsal. It can work with Warfighter Physiological Status Monitoring (WPSM) [2] synergistically by expanding physiological analysis based on the data (signals) acquired from wearable sensors to provide more comprehensive analysis. The potential benefits that IWPSP can provide include (a) Training to personalized safe limits of performance; (b) Mission decision support tool (e.g., optimized route, pacing, soldier status); (c) Physiological controller for performance augmentation systems (e.g., agile microclimate cooling, exoskeleton activation/proprioception); (d) Man-machine interface to distribute workload (i.e., stress management); (e) Materiel testing and acquisition/product selection decision tools; (f) Health and medical management applications (to be used by medical providers); (g) Chemical/biological threat prediction and mitigation; and (h) Health readiness behavioral management.

In this paper, investigations were performed to develop a technology for IWPSP and to build a software system that implements the technology developed. In the technology development, the problem addressed include: (a) Mission scenario modeling; (b) Individual warfighter modeling; (c) Mission activity modeling; (d) Biomechanical analysis; (e) Activity energy expenditure estimation; and (f) Physiological analysis.

TECHNOLOGY DEVELOPMENT

Mission Scenario Modeling

To make IWPSP meaningful to and useful for military applications, the problem needs to be considered under real world conditions. Therefore, we have conceived a typical mission scenario, as shown in Figure 1. The basic elements

of a mission scenario consist of a battlefield including the combat ground at a geolocation, military assets, and local meteorology, a team of warfighters, mission activities, and tasks and actions performed by each warfighter.
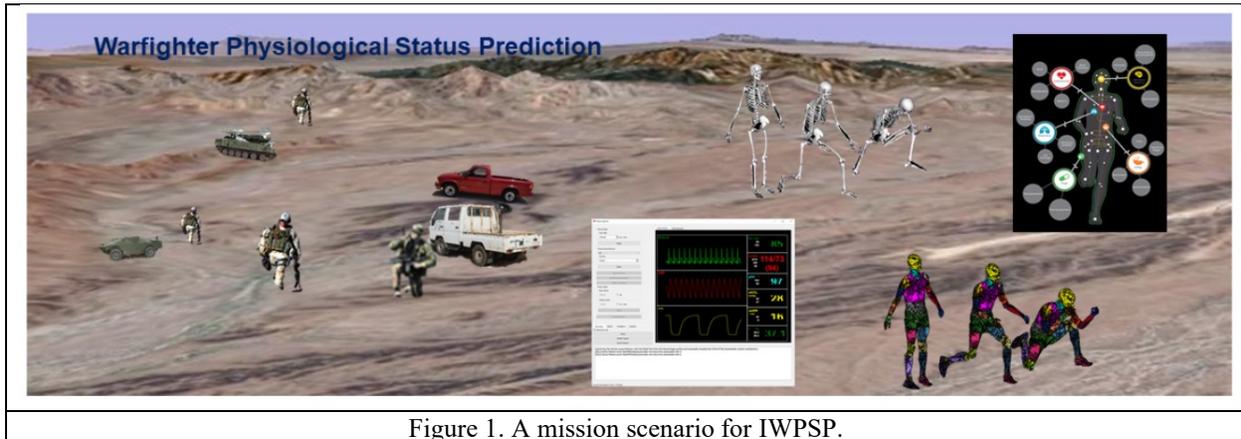

Figure 1. A mission scenario for IWPSP.

Individual Warfighter Modeling

Within a military unit in a mission, each warfighter may exhibit quite different physiological status even taking same tasks under same mission conditions. The difference is due to that each warfighter has unique biomechanical and physiological characteristics. Therefore, each warfighter needs to be modeled individually, as one or a few standard human models are not adequate.   In this study, individual warfighter modeling is leveraged on the IAVCA developed by Zientara and Hoyt at the US Army Research Institute of Environmental Medicine (USARIEM) [4]. Under a small business innovation research (SBIR) program (Phase I and Phase II) sponsored by USARIEM [5], a framework has been created to enhance and convert the IAVCA to become functional models for biomechanical/physiological simulation and analysis, as shown in Figure 2. The framework consists of multiple components which are described as follows.

1. Deriving a musculoskeletal (MS) model from the IAVCA, and then integrating it with OpenSim (an open source software system that lets users develop models of musculoskeletal structures and create dynamic simulations of movement) to simulate the warfighter's kinematics and dynamics.
2. Mapping the IAVCA into a fully functional Full Body Finite Element (FBFE) model and integrating it with LS-DYNA (a commercial FE software package; Livermore Software Technology Corp, Livermore CA) or FEBio (an open source FE software tool) to analyze and predict the warfighter's physical status and biomechanical response under various conditions, such as force, acceleration, vibration, and impact.
3. Using the physical status and Activity Energy Expenditure (AEE) predicted by the biomechanical simulation and other parameters from the IAVCA as the input to Pulse Physiology Engine (PPE), which is an open source software tool developed by Kitware (Clifton Park NY) for physiological analysis, to simulate physiological responses of the warfighter.

Mission Activity Modeling

An individual MS model can be created from the IAVCA for a warfighter by scaling. Whereas this model could be used in OpenSim for forward kinematics and dynamics, technically it is not ready for predicting or creating a mission activity (e.g., marching) with high bio-fidelity. Therefore, mission activity modeling in this study is done via motion replication where an MS model is animated with motion capture (mocap) data. When the motion data captured from one person are used to animate an individual MS model representing another person, motion mapping (or retargeting) is required since two human subjects differ in their body skeleton structures. Retargeting can be done in two ways:

- If mocap data contain marker positions (e.g., TRC file or C3D file), motion mapping can be achieved in OpenSim through marker adjustment.
- If mocap data contain joint angles (e.g., BVH file), an algorithm was created for retargeting the data from the source subject to the target subject.

Biomechanical Analysis

In a mission, a warfighter performs various tasks. While performing a task, the body is subject to force, acceleration, and impact, and metabolic energy is consumed. All these affect warfighter physiological performance and status.

Biomechanical analysis can be performed to predict warfighter biomechanical response in a mission. The MS model and FBFE model derived from the IAVCA can be used to conduct two types of biomechanical analysis with two software tools selected, for example.

- OpenSim: Based on biomechanics principles, OpenSim utilizes a musculoskeletal model to predict kinematics and dynamics and perform inverse kinematics and dynamics as well. By running an MS model in OpenSim, we can predict and analyze human physical responses and performance related to pose and motion.
- Ls-Dyna: By integrating the FBFE model with Ls-Dyna, we can predict and analyze human physical responses and performance under various conditions, such as force, acceleration, vibration, impact, shock wave, heat, and blast.

It should be noted that whereas tools used for biomechanical analysis may differ from each other, their requirements of models are basically the same or similar.
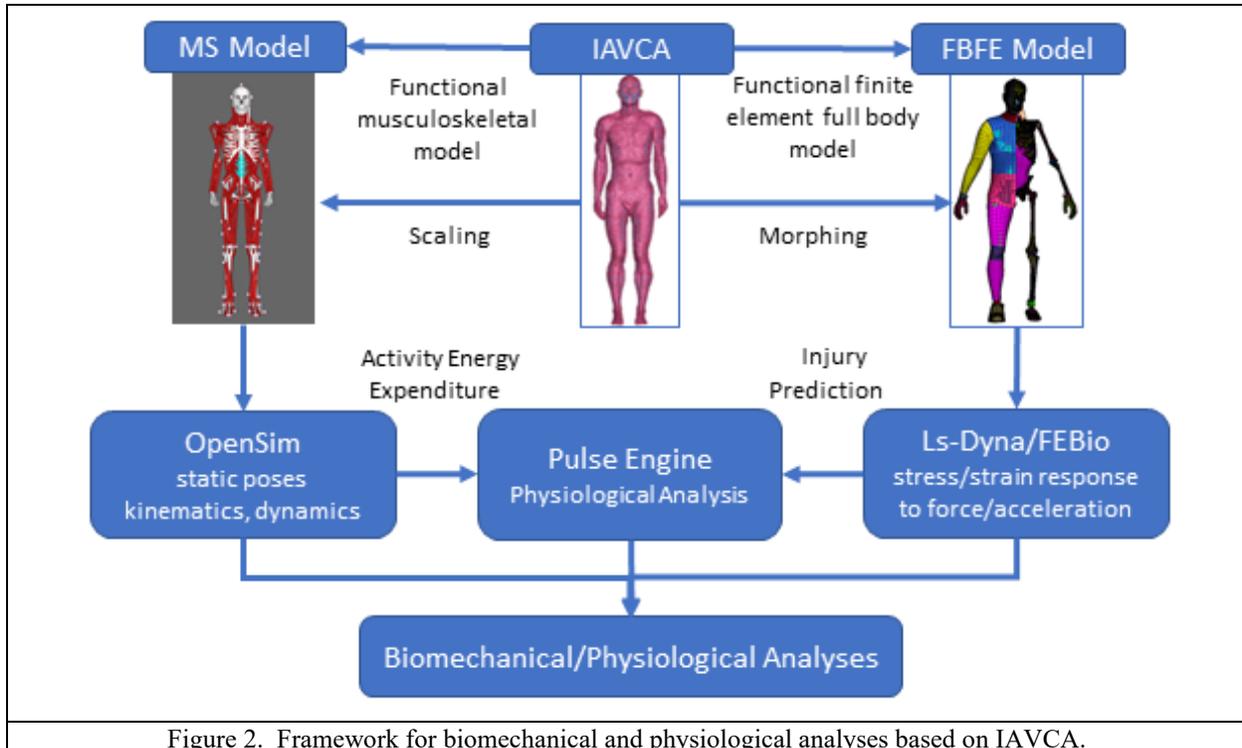

Figure 2. Framework for biomechanical and physiological analyses based on IAVCA.

Activity Energy Expenditure Estimation

Energy expenditure is a metabolic parameter that is fundamental to many applications involving thermal, workload, and injury risk predictions [2]. For example, cold injury risks can be significantly reduced during high energy expenditure with metabolic heat production, while high physical activity levels are increasingly limited in hot environments. The ability to accurately estimate and predict energy demands of human activity is of broad value to a range of communities. Predicting these energy demands has been a historical goal for military applications, athlete populations, as well as for civilian use. Understanding the range and specific amount energy needed to do different tasks has a direct link to nutritional requirements, logistical planning, as well as implications of performance (e.g., how difficult will a certain task be, can it be reasonably done in the time required) [6]. The rate and the time history of energy expenditure for mission tasks have direct effects on the warfighter's physiological performance and status.

The estimation and prediction of activity energy expenditure (AEE) can be handled in different ways with different level of details.

- Regression equations: Researchers have developed many equations to predict level and uphill walking energy expenditure by regression analysis of test data with factorial parameters (e.g., speed, surface grade, and body plus-load mass) [6-10]. In this study, the new Load Carriage Decision Aid (LCDA) graded walking equation developed by Looney et al. [6] is implemented as one method to calculate energy expenditure during standing as well as walking on level, uphill, and downhill slopes. The equation is given by

$$EE \ (W/kg) = 1.44 + 1.94S^{0.43} + 0.24S^4 + 0.34SG \ [1 - 1.05/1.1^{(G+32)}] \qquad (1)$$

Where EE represents the power (Watt) per unit mass (kilogram), S is the walking speed (m/s), and G is the ground grade (%). The equation is a valid predictor of standing and walking energy expenditure in healthy, military-age individuals for the walking speed up to 1.96 m/s and grade between -40% to 45%.

- MEE model: Musculoskeletal modeling can be used to simulate human gait and to calculate the energy expenditure based on a metabolic energy expenditure (MEE) model. The metabolic cost of walking is the energy expended by the human body to move a certain distance. The metabolic cost can be calculated using variables that are studied in gait analysis, such as joint moment, joint power, or muscle force, length, and activation. A study was performed recently to compare seven MEE models [11]. Among them, six models use muscle states (contractile element length, activation, stimulation) to determine the energy rate of the individual muscles [12-17], whereas one calculates the energy rate for each joint instead of each muscle, using the angular velocity and joint moment [18]. Due to its relative simplicity, we choose to use the MEE model presented by [18], which for a gait motion is given by

$$E = \frac{1}{Tmv} \int_{t=0}^{T} \sum_{i=1}^{N_j} \dot{E}_i dt \qquad (2)$$

Where E is in the unit of J/(kg·m), T denotes the motion duration, m the participant's mass, v the speed, N_j the number of joints, and $\dot{E}i$ the energy rate of joint i in W. The energy rate $\dot{E}i$ is given by

$$\dot{E}_i = \dot{h}_i + p_i \qquad (3)$$

Where $\dot{h}_i$ is the heat rate, and the power p_i at joint i is the product of the joint moment and angular velocity:

$$\boldsymbol{p_i = M_i \dot{\theta}_i} \qquad (4)$$

It should be pointed out that whereas MEE models may be extended to other body movements/actions, the validity and accuracy of the MEE prediction depends on MS modeling that is able to provide highly bio-fidelic simulation of muscle/joint forces for a human activity. It is still an open problem to estimate/predict MEE for general actions other than gait motion.

Physiological Analysis

Several software tools are available for physiological analysis, including BioGears (https://www.biogearsengine.com/), HumMod (http://hummod.org/), VPH (https://www.vph-institute.org/), and Pulse Physiology Engine (https://pulse.kitware.com). After careful comparison and evaluation of these tools, we choose to use PPE as the software tool for physiological status analysis and prediction in this study. As shown in Figure 3 (a), PPE is a C++ based, open source, multi-platform (Windows, Mac, and Linux), comprehensive human physiology simulator that drives medical education, research, and training technologies. The engine enables accurate and consistent physiology simulation across the medical community. The engine can be used as a standalone application or integrated with simulators, sensor interfaces, and models of all fidelities.

The energy system in PPE provides a methodology for both thermal and metabolic regulation within the body. As shown in Figure 3 (b), heat transfer is modeled by a body thermal circuit that is connected to the environment circuit. A heat source at the core of the body circuit represents the metabolic heat production. In addition to generating heat, the dynamic metabolic rate is also used to compute the metabolic production and consumption rates of gases and other substances in the body. The variations in the external environment or physical activity can lead to changes in the core temperature, triggering thermal feedback. The exercise capacity of the body is physiologically and psychologically limited. The amount of work produced by the exercise action is limited by the fatigue model which is represented as a system of interconnected energy storage compartments, as shown in Figure 3 (c).
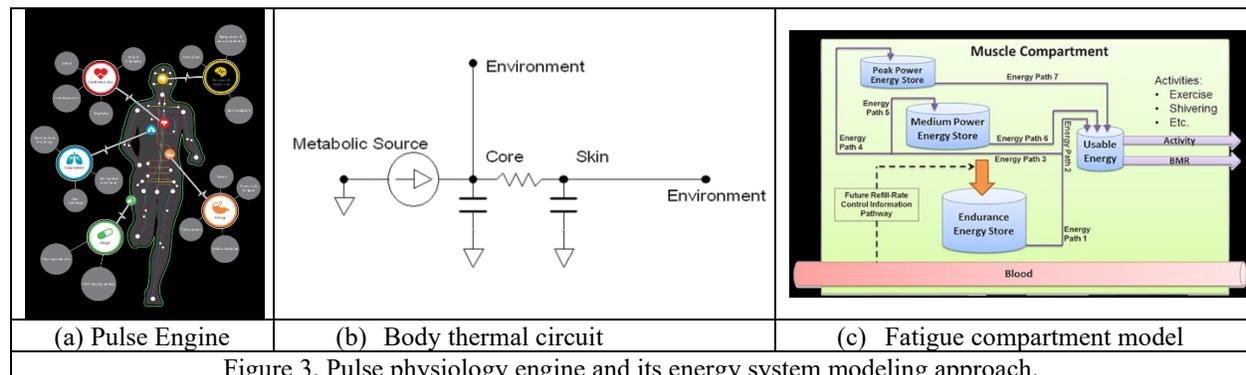

(a) Pulse Engine	(b) Body thermal circuit	(c) Fatigue compartment model

Figure 3. Pulse physiology engine and its energy system modeling approach.

When PPE is used in this study for IWPSP, three factors are accounted: physical and physiological characteristics of an individual warfighter, environment conditions of a battlefield, and mission tasks (exercises) that induce metabolic energy expenditure and fatigue.

SOFTWARE SYSTEM CONSTRUCTION

To implement the technology developed for IWPSP, a software system was constructed, as shown in Figure 4. The system was built on the top of Unity as a Unity game to utilize capabilities and functions provided by Unity. For the integration of PPE with Unity, a C# plug-in is provided. The plug-in has two main features:

- VitalMonitor, which provides a Pulse Engine Driver to calculate the status and a viewer to view patient's status. Pulse Engine Driver is required to load a JSON file that records a patient status in the 0th sec state. Pulse Unity can work with up to 10 JSON files of patients.
- PulseActionOnClick, which allows user to add an action to patient. Since it does not have the action of Exercise that we want, we modified the code and added it.

In the software system, the IWPSP can be conducted for up to 10 warfighters simultaneously with the status monitored and displayed for each of them.
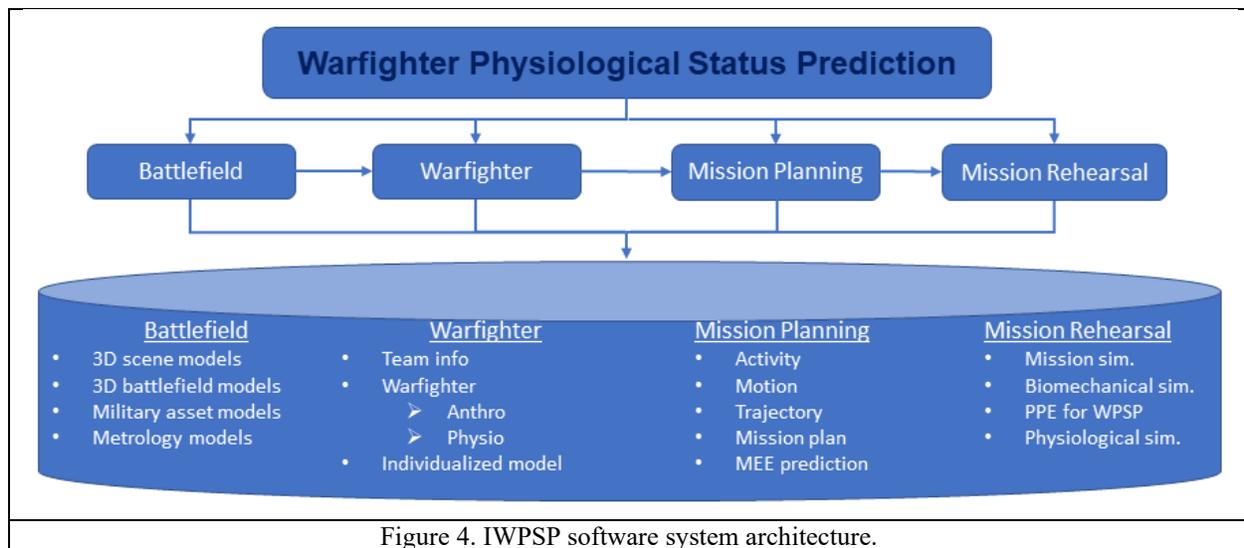

Figure 4. IWPSP software system architecture.

Battlefield Modeling

Environment conditions, such as the altitude of geolocation, slope of ground, and ambient temperature affect human physiological status from various aspects including metabolic energy expenditure, heat transfer and body thermal strain, and muscular-skeleton injury. Therefore, battlefield modeling is required to provide realistic and accurate representation of environment conditions of a battlefield. Three factors are considered: terrain, military assets, and local metrology.

- 3D terrain modeling. A geolocation can be identified by a global positioning system (GPS) signal, an address (on google map), or a pair of latitude and longitude. Several software tools are available to create a 3D map or a 3D terrain model of a geolocation, such as 3D Map Generator Atlas which is a plug-in to PhotoShop. Among them, Mapbox is used as the tool for 3D terrain model generation in this study as it has a Software Development Kit (SDK) for Unity. As shown in Figure 5, for an identified geolocation, different terrain models can be created at different zoom levels.
- Military asset modeling. A military function utilizes a unique set of equipment for their missions. For instance, tanks and combat vehicles are often used by army in their missions. Military assets, as an important component of a battlefield, plays various roles in warfighters' mission activities. The modeling of military assets can be represented by 3D object models.
- Local metrology. The attributes of local metrology that affect warfighters' physiological performance include temperature, humidity, wind speed, and weather conditions (e. g., sunny, cloudy, rainy, snowy, windy, etc.). All these parameters need to be determined and recorded in a data file.
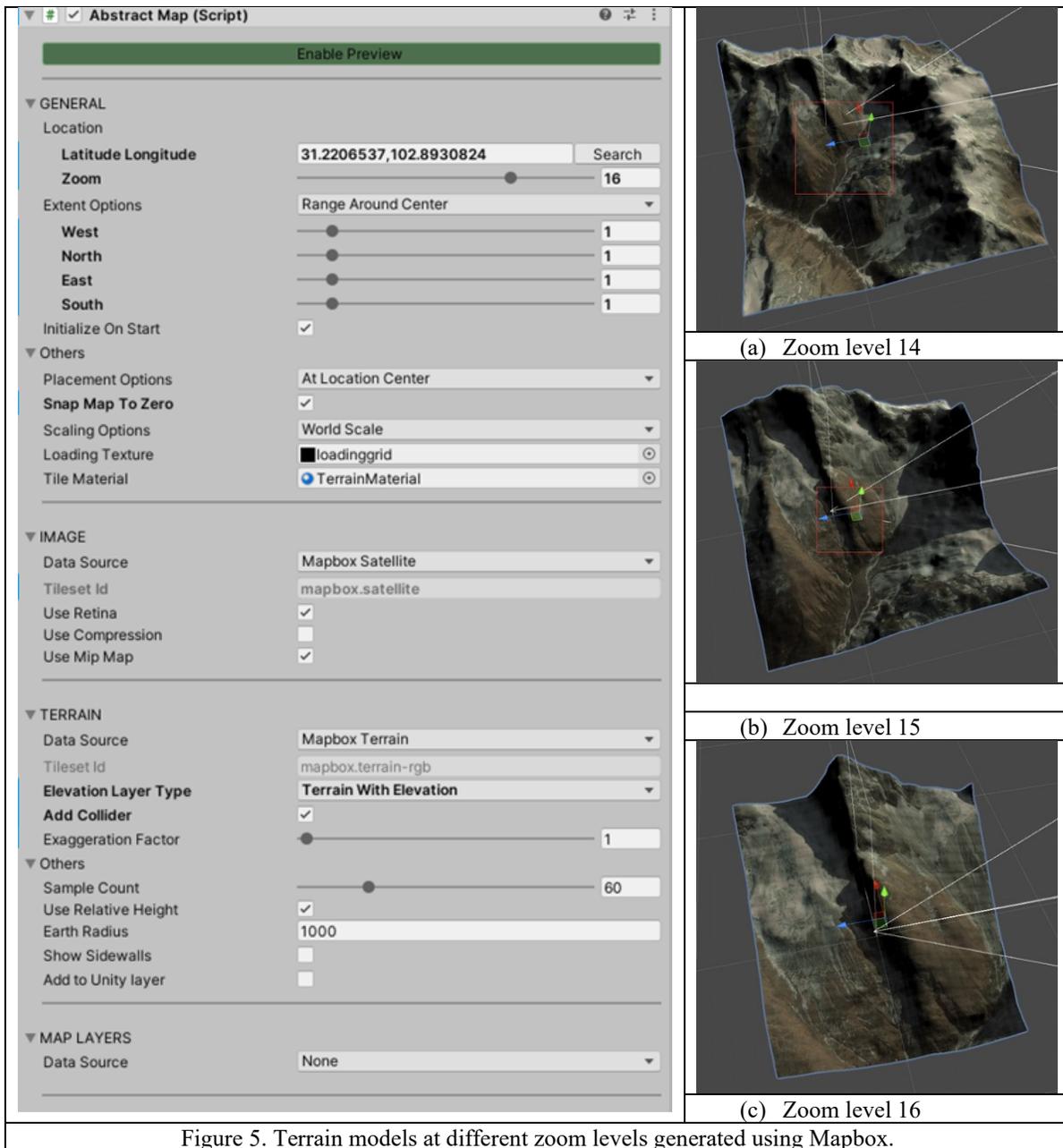
(a) Zoom level 14

(b) Zoom level 15

(c) Zoom level 16

Figure 5. Terrain models at different zoom levels generated using Mapbox.

Warfighter Modeling

The IAVCA is used for warfighter modeling. An IAVCA model can be created by fitting its template to the 3D body scan of a warfighter. Other parameters to be defined in this module include anthropometric parameters (gender, age, height, and weight), physiological parameters (body fat fraction, baseline heart rate, baseline systolic/diastolic arterial pressure, and baseline respiration rate), and the personal role in a team for team activities.

Mission Planning

This module is designed to allow a user to do mission planning. It allows a user to select a mission activity for a military unit (e.g., a squad), to assign tasks to each warfighter, and to put body gears on a warfighter. Then, it allows a user to position each warfighter in the battlefield by defining its coordinates and orientation or by manually placing the avatar into the 3D terrain model, to determine the starting and ending points and trajectory of a motion or define a region for an activity, and to specify the speed, intensity, and duration of a motion or activity.

Mission Rehearsal

This module allows a user to conduct mission rehearsal virtually. Several options are provided for users to choose, including Unity game play, biomechanical simulation (OpenSim or Ls-Dyna), physiological simulation (PPE), and all integrated. The module provides view control to view battlefield scenario from different view angles and distances.

CASE STUDY

A case study was performed to test the technology and software system developed. The case is the mission of a squad marching through a rough terrain with carried body gears. The case (mission) was generated via the following steps:

1.   The geolocation of the battlefield is determined by latitude and longitude. A 3-D terrain model is created for this geolocation. On the top of terrain surface are placed 3D polygon models of bushes, trees, rocks, and military assets, as shown in Figure 6. Parameters are assigned to define the local metrology, including temperature, humidity, wind speed, and weather condition.

2.   Anthropometrical and physiological parameters are assigned to each warfighter of the squad. In the Unity game, each warfighter is represented by an avatar scaled from a template avatar. For biomechanical analysis, the MS model of each warfighter can be created from the template MS model by scaling, and the FBFE model of each warfighter can be created from the template FBFE model by morphing.

3.   The role of each warfighter in this mission is the same. Each warfighter is assumed to carry the same body gears with the same total carried load.

4.   Each warfighter is placed in the field with the initial position and orientation to march forward along the trajectory defined for each, as shown in Figure 7. The motion of each warfighter is replicated via animating the avatar in Unity game, and then through inverse kinematic and inverse dynamics in OpenSim with the MS model.

5.   The metabolic energy expenditure is calculated for each warfighter using two methods described above: the empirical regression equation (LCDA) and the joint space MEE model.

6.   A JSON file is created for each warfighter to include the data of environment, patient (warfighter), and exercise (activity). This file is used as the input file to PPE.

7.   The PPE is called from Unity and initialized for each warfighter to perform physiological analysis.

8.   The results from PPE are fed back to Unit. The vital sign signals can be displayed in real time for each warfighter, as shown in Figure 8.

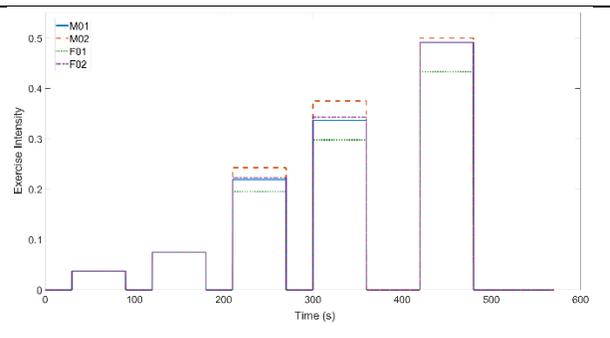|	
Figure 6. Battlefield modeling	Figure 7. Warfighter and mission planning.
Figure 8. Real-time vital signs for each warfighter.	Figure 9. Exercise intensity level during marching.

From the squad four warfighters are selected with their anthropometric/physiological parameters listed in Table 1, which include gender (G), age, weight (Wt), height (Ht), body fat fraction (BFF), heart rate baseline (HRB), diastolic arterial pressure baseline (DAPB), systolic arterial pressure baseline (SAPB), and carried load (CL). Assume that these warfighters are marching on a hill with the varied grades (0, 5%, 10%) at the speed of 1.1 m/s, following the activity sequence described in Table 2 where rest is the state of standing, LLA-1 and LLA-2 represent lower level activity at the intensity level of 0.0375 and 0.075, respectively. The metabolic energy expenditure is estimated for each warfighter in terms of power (W), with the results given in Table 1 also. In terms of the maximum human power defined by PPE (1200 W), the exercise intensity versus time for each warfighter is plotted in Figure 9. Among the results obtained from PPE, six physiological status signals are displayed in Figure 10 for those four warfighters.

Table 1. Parameters for the case study.

ID	G	Age (y)	Wt(kg)	Ht (cm)	BFF	HRB (1/min)	DAPB (mmHg)	SAPB (mmHg)	C L (kg)	P (W)-rest	P(W)-0%	P(W)-5%	P(W)-10%
M01	M	22	67	175	0.21	72	73.5	114	27.24	96.48	359.3	500.3	686.2
M02	M	26	79	185	0.21	72	73.5	114	27.24	113.76	405.0	564.0	773.5
F01	F	22	55	160	0.28	72	73.5	114	27.24	79.2	313.5	436.6	598.8
F02	F	26	69	170	0.28	72	73.5	114	27.24	99.36	366.9	510.9	700.7

Table 2. Activity sequence and duration.

Duration (s)	0-30	31-90	91-120	121-180	181-210	211-270	271-300	301-360	361-420	421-480	481-570
Activity	rest	LLA-1	rest	LLA-2	rest	1.1 m/s @ 0%	rest	1.1 m/s @ 5%	rest	1.1 m/s @10%	rest

DISCUSSION

Variation and Individualization
Physiological status is personal, depending on individual physical and physiological characteristics. While performing same tasks under same environment, warfighters physiological performance may differ substantially from each other, as shown in Figure 10. Therefore, representing individual characteristics in physiological status prediction becomes necessary. The bio-fidelity of the individualized models can be further improved with the utilization of medical image data with more details, such as CT scan. However, there is trade-off between the level of details and the cost of modeling.

Realism and Fidelity
As a mission planning tool, it is important to create a mission scenario that provides sufficient realism of real-world missions. Thanks to the recent advancement in 3D map/terrain generation, we can quickly create a realistic 3D terrain model for a prescribed geolocation. However, to improve the realism of a battlefield model, we need to place 3D polygon models of bushes, trees, fences, rocks, buildings, military assets, etc. on the top of a terrain surface, which requires extensive effort. The fidelity of models is a key factor for the validity of prediction. In IWPSP, the fidelity of modeling involves the following aspects:

- Human activity modeling: As a warfighter may perform a wide spectrum of mission tasks, it is challenging for human activity modeling to model these mission tasks with high fidelity. The challenge comes from the motion/action performed during mission, military equipment used, military gears on the body, the contact between a warfighter and his surrounding environment, and the interactions among team members.

- Biomechanical analysis: When the MS model and FBFE model are used for biomechanical analysis, the validity of analysis results relies on the bio-fidelity of the MS model and FBFE model derived from the IAVCA. Whereas the IAVCA provides sound approximate representation of human anatomy and biomechanical features, the bio-fidelity is limited by the biomechanical properties of joints, bones, soft tissues, etc., which are also personally dependent.

- MEE prediction: Whereas the estimation and prediction of MEE can be handled in different ways with different level of details, empirical equations can only deal with human movement with gait. Theoretically, the model-based methods can handle MEE for any body movements, further investigations are required to validate these methods and to validate the results of inverse kinematics and inverse dynamics.

- Physiological analysis: In IWPSP, PEE is utilized for physiological analysis. As an open source software tool, PEE has been validated by its developers and its users through various applications. Currently, PEE assumes that the maximum power that a human can generate is 1200 W, and the intensity of an exercise (action) is measured relatively to this limit. This assumption may need to be modified to account for the variation among different warfighters and the dependency on personal training.
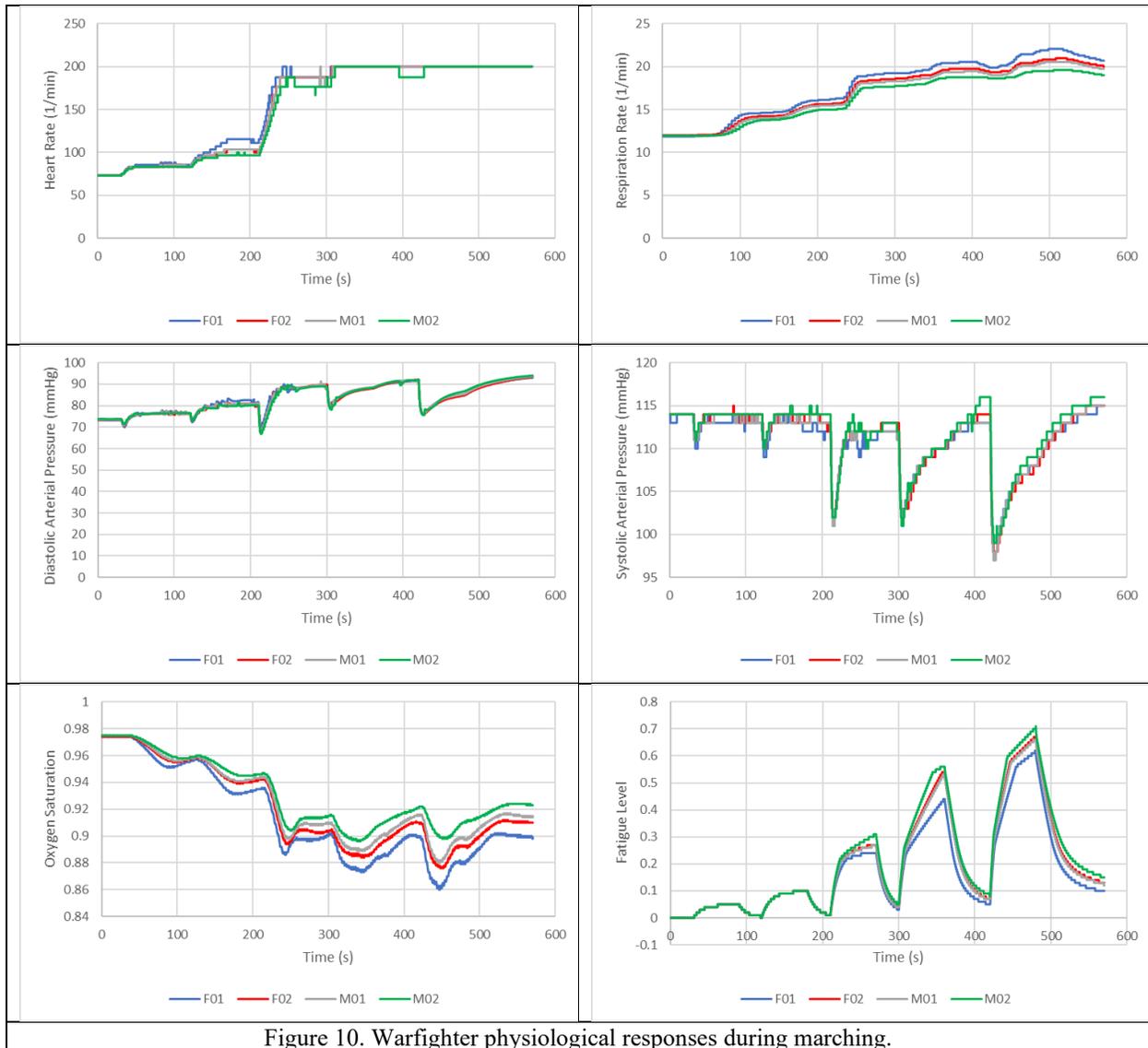
Figure 10. Warfighter physiological responses during marching.

Physiological status monitoring and prediction

Whereas the real-time physiological status monitoring (RT-PSM) based on wearable sensors technology has become an enabling technology for warfighters [2], warfighter physiological status prediction is still important as it can be used in mission planning. Besides, wearable sensors can only acquire limited measurements of body signals. However, the wearable sensor data can be combined with other personal data and then fed into PEE to obtain a comprehensive analysis and assessment of the person's physiological status. The combination of RT-PSM with IWPSP can not only turn sensor data into useful and actionable knowledge, but also expand the coverage of physiological status which otherwise would not be obtainable with sensors.

CONCLUSIONS

A technology was developed in this paper to predict individual warfighter physiological status, which includes mission scenario modeling, individual warfighter modeling, mission activity modeling, biomechanical analysis, activity energy expenditure estimation, and physiological analysis. A software system was built to implement the technology, which consists of four modules (battlefield, warfighter, mission planning, and mission rehearsal) and a database. A case study was performed to test and demonstrate the functions of the software system. The results of case study show that the goal of IWPSP can be achieved with the technology developed and that the software system has the initial capabilities for IWPSP.

DISCLAIMER

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