Warfighter Digital Twins for Simulating Mission Performance

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ABSTRACT

Recently the concept of a "digital twin" has emerged, which is defined as a virtual model of a specific physical system that is continuously updated using sensor data. However, human digital twins have not been utilized as extensively, largely due to a lack of software tools that provide virtual models of humans with the requisite medical fidelity. In this effort, a digital warfighter avatar simulation platform has been developed that can be used to assess factors such as: gender, anthropometry, biomechanics, exercise intensity (EI), and environment (altitude, heat, cold, and humidity) using computational simulations. The platform allows simulation of a mission scenario with military relevant activities and environments. The simulated scenario is visualized with live-streamed biomechanics and physiological factors related to injury and human performance: muscle force, fatigue, joint range of motion, loading, metabolic energy expenditure (MEE), EI, heart rate, breathing rate, blood oxygenation, and core temperature. OpenSim was used to simulate biomechanics and BioGears to simulate physiology of digital twins during mission scenarios, which are planned and visualized in the Unity 3D game engine. Male and female avatars can be scaled to represent both anthropometry and strength of a given individual. In addition, clothing (with thermal properties) and equipment (e.g., ruck sack) can be added to the avatars. MEE and muscle fatigue algorithms have been incorporated. Predictive human movement algorithms have been developed to allow simulation of military relevant motions without requiring experimental data as input. Example mission scenarios have been simulated, such as a ruck march, and the digital warfighter avatar responded as expected to factors such as amount of load carried. MEE estimates were compared to experimental data and agreed well with calculations using the Pandolf and Load Carriage Decision Aid (LCDA) equations. In the future, virtual human avatars can be integrated into existing mission planning or real-time health monitoring applications. Simulations of an entire squad performing a planned mission could provide a "mission performance forecast" to assess individual fatigue levels and the associated impact on mission performance. Real-time physiological data could then be used to monitor actual physiological response and performance during the mission using the forecast as a baseline.

ABOUT THE AUTHORS

Dr. Paulien Roos leads the biomechanics research group at the BEM division of CFD Research. She has worked in the field of biomechanics, injury prevention/ prediction, and rehabilitation her entire career. She has led multiple successful programs looking at rehabilitation, injury prevention and human performance. She was the PI on the Sequential Phase II SBIR project that forms the base of the proposed work. She has experience bringing products developed under SBIR funds to market, through the startup TheraVista Health that she co-founded (with Dr. Pickle). She holds a PhD in Biomechanics from the University of Bath (UK, 2007). She held postdoctoral and academic positions at the University of Texas at Austin and Cardiff University.

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BACKGROUND

Effectively planning and executing military missions requires understanding human performance and how particular individuals will perform under strenuous tasks in potentially extreme conditions. Human subjects research (experiment-based) in the military is generally performed to gain insight into factors that influence human performance. However, human subjects research has several limitations. Experiments are costly and time-consuming, requiring participants to travel either to laboratory facilities or geographic locations (e.g., mountains, desert) for field tests. Sensors are only capable of measuring a subset of all phenomena of interest, and there are frequently practical issues with lost data due to hardware malfunction. Certain missions, such as those that may induce musculoskeletal injury or adverse physiological responses such as heat illness, are often impossible to safely replicate in controlled experiments. Finally, it can be challenging to extrapolate scientific findings to actual warfighter performance during a specific mission. Variables such as terrain, temperature, physical fitness, and altitude can make it difficult to predict how a particular individual may perform.

Computer simulations of digital human avatars offer a method for studying human performance and injury risk that is not subject to the limitations noted above. Computer simulations can be performed cost-effectively for a range of different conditions. Comprehensive data results representing the internal state of the body can be generated that is more extensive than what can be measured by sensors alone. Although simulations have their own limitations, such as modeling assumptions and simplifications, the need for validation, and technical complexity, simulations provide a way to estimate human response that can guide experimental design or provide “human performance forecasts” for mission planning. A complete virtual human comprising high-fidelity biomechanics and physiology would provide the ability to simulate individuals with specific anthropometric and physiological characteristics performing a prescribed mission. However, there are currently limited tools available for such a mission planning application. Computer simulations are typically used for analysis of controlled experiments, such as walking on a treadmill. New tools and approaches are needed for generating simulations of the complexity and duration of real-world missions.

While computer simulations have historically been used across many fields and industries to inform product design, development, and testing, more recently the concept of a “digital twin” has emerged. A digital twin is defined as a virtual model of a specific physical system that is continuously updated using sensor data. Thus, in contrast to a simulation, which sets the initial conditions of the system and then simulates its behavior, the virtual model in a digital twin is constantly updated and adjusted to ensure an accurate depiction of the actual state of a specific physical system. Digital twins are powerful tools for leveraging modern computing power to provide continuous monitoring of the internal state of a physical system, and more effectively detect risk of malfunction or failure. Digital twins have achieved significant adoption in industries such as aerospace and transportation. However, human digital twins have not been utilized as extensively, largely due to a lack of software tools that provide virtual models of humans with the requisite medical fidelity.

The objective of the work reported in this paper was to develop and test virtual human avatars suitable for use in human digital twin applications. The scope of this effort was constrained to the virtual portion of the digital twin. Because there is currently a lack of software tools available for use in human digital twin applications, suitable virtual human models must first be developed and tested prior to incorporating sensor data for real-time monitoring. The ultimate long-term goal of this work, however, is to incorporate sensor data to create a true digital twin of a human. Human digital twins would have significant utility in human performance applications. For example, future mission planning could be conducted using a virtual model of a specific individual that has been continuously updated to reflect their current levels of fitness, hydration, and fatigue.

In this paper we describe the methods and tools being used to develop virtual human avatars for use in human performance research and mission planning. Results from testing of the various components of the virtual humans in representative environments are presented. We conclude with a discussion on the current state of the technology and future directions.

METHODS

An overview of the tools used to develop the virtual human avatars is shown in Figure 1. Open-source engines were selected for incorporating simulated biomechanics and physiology. The usage of open-source tools will facilitate rapid integration of new advances in the state-of-the-art. In addition, many researchers are already familiar with these tools. For visualization, human avatars with complete internal anatomy developed by the US Army Research Institute of Environmental Medicine (USARIEM) (Zientara & Hoyt, 2016) were used. The various elements were all integrated in the Unity3D gaming engine (Unity Technologies), a widely used platform for developing applications involving virtual humans and simulated mission planning. Each individual element of the framework is described in more detail below.

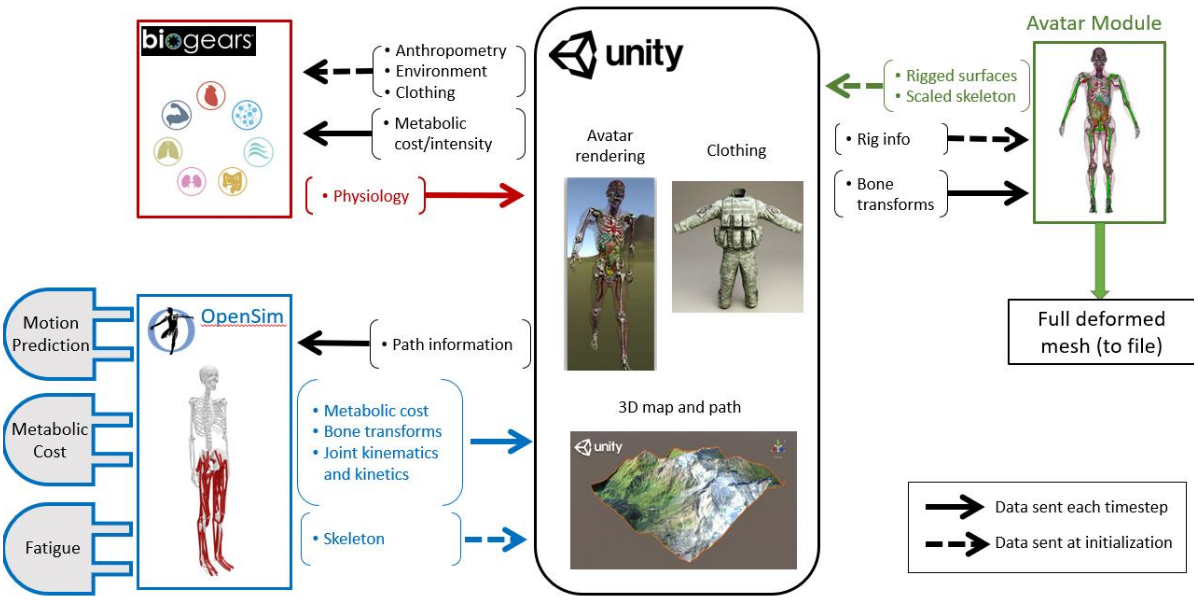


Figure 1: Diagram overview of the software platform for simulating mission performance.

Physiology

The BioGears computational physiology engine (Baird et al., 2020) was selected for simulating physiology. BioGears is an open-source tool developed by the University of Utah. In BioGears, individual physiological systems (e.g., respiratory, cardiovascular) are represented by physics-based lumped parameter models and control system feedback loops. Each individual physiology system has key parameters which have been validated experimentally. BioGears is written in C++ but provides basic functionality for generating C# bindings, which was modified and extended to utilize BioGears within the Unity gaming engine.

A key input to the BioGears engine is exercise intensity, which is the dynamically varying input parameter that drives an exercise simulation in BioGears. Other model parameters, such as age, sex, V02 max, clothing thermal properties, ambient temperature, and atmospheric pressure can be modified in the BioGears engine.

Biomechanics

The OpenSim software (Seth et al., 2018) was selected for simulating biomechanics. OpenSim is an open-source tool developed by Stanford University. A number of validated musculoskeletal models are available for OpenSim, such as a whole-body model with lower extremity musculature (Rajagopal et al., 2016). OpenSim is written in C++ and provides prebuilt bindings for Python, Java, and Matlab. Functionality was added for generating C# bindings to utilize OpenSim directly from within a Unity-based application.

Predictive Movement Generation

A key objective of the virtual human avatars is to be able to generate movement simulations without the need for experimental motion capture data from human subjects. The ultimate goal is to be able to generate an avatar of arbitrary anthropometric characteristics and then command it to navigate an arbitrary path (e.g., varying terrain and speed). Conventional simulations in OpenSim require motion capture and ground reaction force data as input (Thelen & Anderson, 2006). The recently added Moco tool (Dembia et al., 2019) can generate simulations in the absence of input data, but predictive simulations in Moco are limited to short duration movements (e.g., a single stride of walking).

To address this limitation of OpenSim, new functionality for task space control was implemented. Task space control involves defining motions by end effector (e.g., hand or foot) trajectories rather than by joint angle trajectories. Task can be prioritized so that secondary tasks (e.g., moving the body forward) do not interfere with the most crucial tasks (e.g., maintaining balance to avoid falling). Task space control is widely used in whole-body control of bipedal robots (Sentis & Khatib, 2006). Prior work has implemented task space control in OpenSim (Stanev & Moustakas, 2017), but only for models which were fixed to the ground (e.g., for simulating reaching tasks). We extended the existing implementations to support floating-base kinematics, in which the base segment of the model (e.g., the pelvis) is free to move in space (Mistry & Schaal, 2015). Predictive simulations of walking were generated using tasks specifying the position of the feet and pelvis as well as the orientation of the torso.

Joint-Based Metabolic Energy Expenditure

As noted previously, a key input to the BioGears engine is exercise intensity (EI). Because the avatars are intended for use in simulating arbitrary movements, it was desired to compute EI from the movement simulated by the OpenSim model. EI can be computed from metabolic energy expenditure (MEE). First, MEE is converted to VO2 using the individual's VO2 max. It is assumed that 5 kcal of energy are expended for every liter of O2 consumed (Porcari et al., 2015). The conversion from kcal/min to Watts is 69.78 W/kcal/min. According to the BioGears documentation, an individual's VO2 max is defined as corresponding to an EI of 0.6. Using these values, the following equations can be used to calculate exercise intensity from MEE:

$$VO_{2,\ current} = \frac{MEE}{69.78 * 5}$$

$$EI = \frac{VO_{2,current}}{VO_{2,max}} * 0.6$$

OpenSim provides muscle-based metabolic energy models (Bhargava et al., 2004; Umberger et al., 2003), but these calculations rely on computationally intensive muscle-driven simulations. In order to calculate MEE during more computationally efficient joint torque-driven simulations, an OpenSim plugin was developed to calculate MEE from joint torques using previously published mathematical models (Cruz & Yang, 2022). The computed MEE values were then used as input to the previous equations to compute an EI value to drive the BioGears physiology engine.

Integration with Unity

To facilitate usage of the virtual human avatars in mission simulation applications, all functionality was integrated into the Unity gaming engine. C# bindings were generated for OpenSim and BioGears. Visualization utilities were created for animating both the OpenSim skeleton model as well as internal anatomy from the USARIEM avatars. User controls and real-time readouts of biomechanical and physiological signals were implemented in Unity.

Analysis

Analysis was performed of individual components of the virtual human avatars. The task space control framework was used to generate a walking simulation using only high-level tasks (Table 1) and no experimental data as input.

Table 1: Task definitions used to generate simulated walking gait. Priority 0 is the highest priority level.

Priority level	Task	Type
0	Torso orientation	Orientation
0	Pelvis forward progression	Position
0	Pelvis height	Position
0	Pelvis orientation	Orientation
1	Swing foot position	Position
1	Swing foot orientation	Orientation

Results from the joint-based MEE plugin were compared to the commonly used Load Carriage Decision Aid (LCDA) and Pandolf equations (Pandolf et al., 2011). To conduct initial validation of the joint-based MEE calculations, data were collected from one male participant (age 25, weight 79.4 kg, height 1.88 m) who provided written informed consent to participate in an experimental protocol approved by the Institutional Review Board at CFD Research Corporation. The experiment included five level-ground walking trials: unloaded walking at 0.8, 1.3, and 1.8 m/s and loaded walking at 1.3 m/s with backpack loads of 9 and 18 kg. Motion data were collected during the trials using an Xsens MVN Awinda motion capture system (Movella, Henderson, Nevada, USA). For the loaded trials, the subject was additionally outfitted with a backpack containing dumbbells of the prescribed weights. To calculate joint torques, OpenSim Moco (Dembia et al., 2019) was used to generate torque-driven simulations of the recorded movement.

A BioGears simulation was performed for a long-duration alpine ruck march to evaluate the ability of the BioGears engine to simulate extended missions. No experimental data were collected, but temperature and altitude data from the Pikes Peak Highway were used to create a hypothetical high-alpine route for a ruck march.

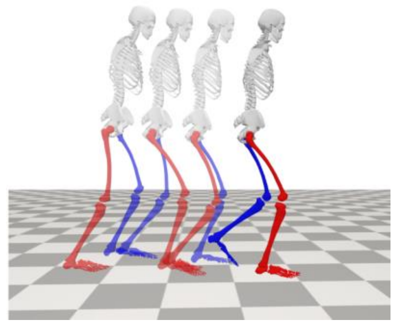
RESULTS

Predictive Movement Simulation

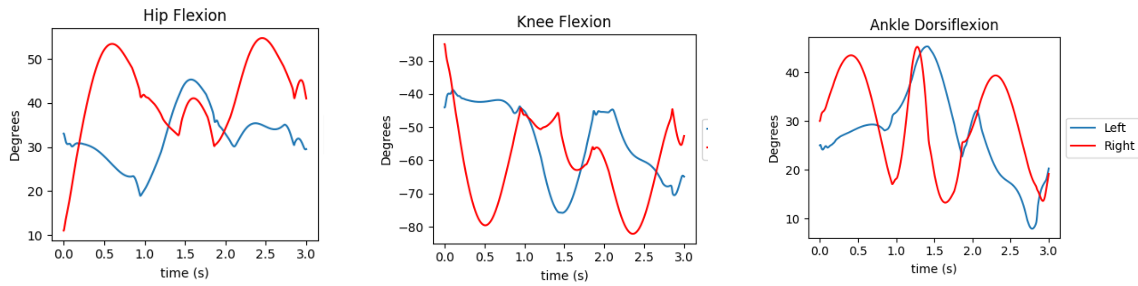
A walking simulation was generated using task space control. The simulation was evaluated by investigating the joint angles (hip flexion/extension, knee flexion/extension, and ankle dorsi/plantarflexion) and the ground reaction forces (Figure 2). The simulation was visually similar to typical human gait (Figure 2a), but exhibited unrealistic joint angle trajectories and spikes in the ground reaction forces.

Joint-Based Metabolic Energy Expenditure

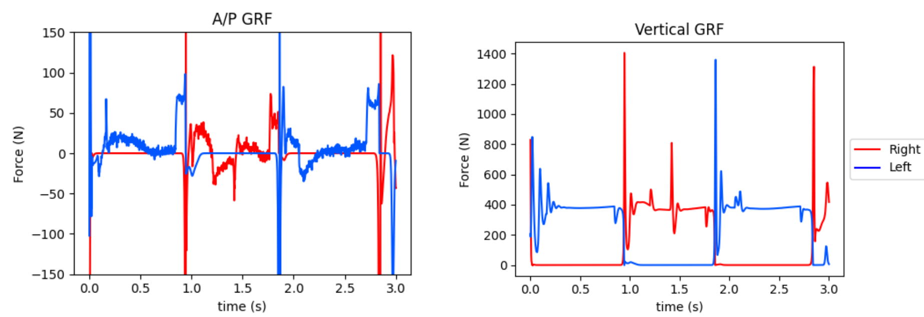
Overall, the joint-based model produced higher MEE estimates than the regression-based models for all conditions for a single subject (Figure 3). The LCDA estimates were generally similar to the Pandolf equation (less than 6% difference) except in the 0.8 m/s trial, in which the LCDA estimate was 23% higher. The Pandolf equation has been shown to underestimate MEE (Drain et al., 2017), suggesting that MEE estimates from both Pandolf and LCDA may be lower than actual MEE.



(a)



(b)



(c)

Figure 2: Gait controller results for the left leg (blue) and right leg (red). Two complete gait cycles were simulated (a). Kinematics of the left and right leg over the course of the stride were output from the simulation (b), along with ground reaction force patterns for the left and right leg (c).

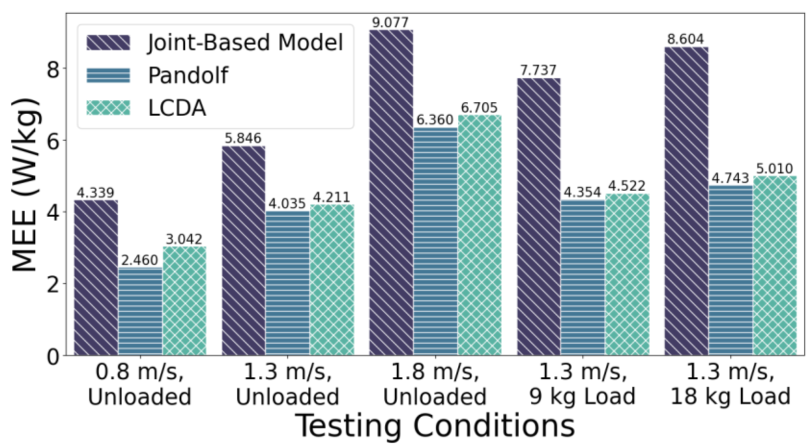


Figure 3: Plot of predicted metabolic energy expenditure (MEE) for various speeds and rucksack loads. The joint-based model was compared to the Pandolf and Load Carriage Decision Aid (LCDA) regression-based models.

Simulated Physiology

The ability of the BioGears engine to simulate real-world scenarios was tested by performing a simulation of an alpine ruck march. An elevation profile was generated using data from the Pikes Peak highway (maximum elevation 14,115 feet). Walking speed was 0.8 m/s speed, with a 10-minute rest every 50 minutes. The change in altitude was represented by a change in atmospheric pressure and a change in environmental temperature. The clothing parameter was set to 1 CLO (similar to Battle Dress Uniform). Rucksack weights of 30% and 40% body weight were added.

Results from the BioGears physiology simulation are shown in (Figure 4). The BioGears engine successfully completed the simulation of a >12 hour hike. Simulated heart rate increased with elevation gain and was also higher when a ruck sack was added in the simulation. The model also responded as expected during regularly spaced rest periods, with an observed decrease in heart rate.

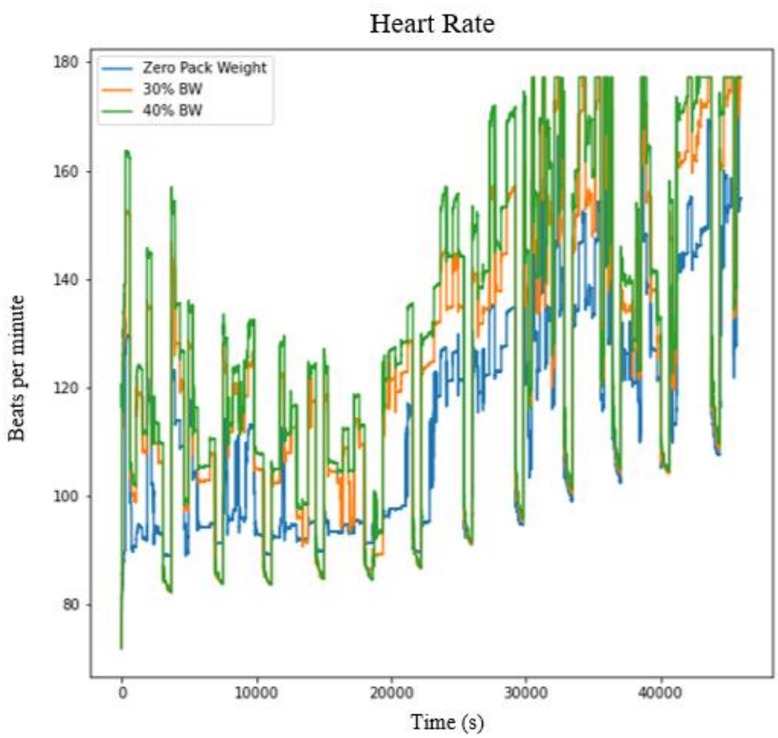


Figure 4: Results of a long-duration (12 hour) simulated ruck march in BioGears. The simulation was repeated for no pack, pack with 30% body weight (BW), and pack with 40% body weight. Altitude and associated parameters varied from 7,000 feet to 14,000 feet in accordance with data from the Pikes Peak Highway as a representative case.

Integration in Unity

All components were successfully integrated into Unity. The application is compatible with Windows 10, and was tested on a desktop with a 3.40 GHz 13th Gen Intel(R) Core(TM) i7-13700K processor and 32 GB of RAM. The complete virtual human avatar (biomechanics, physiology, visualized anatomy) can be loaded and simulated within the Unity-based software application (Figure 5a). User controls were added for adjusting environmental settings as well as human model parameters (Figure 5b,c). Three tabs were created for adjusting and viewing the various components of an avatar simulation: environment, physiology, and dynamics. In the Environment tab, the user can adjust properties such as gravity (e.g. for simulated space missions or high-g aircraft maneuvers), altitude (which controls environmental oxygen levels), ambient temperature, and humidity. In the Physiology tab, the avatar's biological sex, fitness level, anthropometry, age, VO2 max, resting heart rate, and resting skin temperature can be adjusted. The dynamics tab is intended for use in modifying biomechanical characteristics (e.g., strength), but these features have not yet been implemented. During a simulation, the Physiology and Dynamics tabs also provide real-time displays of selected metrics. OpenSim musculoskeletal models can be loaded and visualized in Unity using the generated C# bindings (Figure 5d). The physics of the musculoskeletal simulation are handled by the OpenSim engine (not Unity's physics engine) enabling direct usage of all OpenSim functionality (such as muscle models and joint definitions).

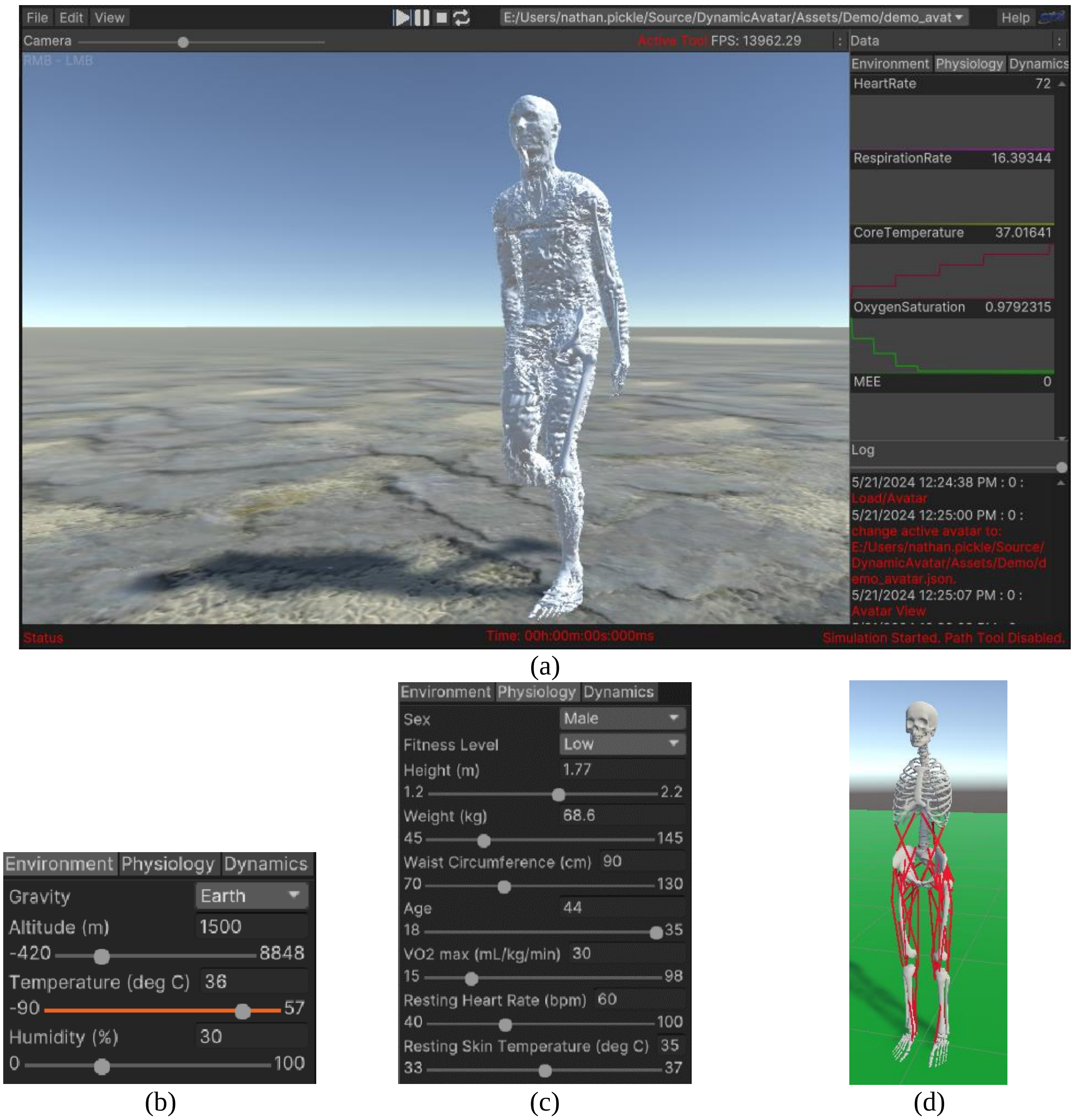


Figure 5: Overview of the Unity-based software. A complete avatar comprising visual anatomy from medical scans, OpenSim-based biomechanics, and BioGears-based physiology can be loaded and simulated (a). Interactive tabs allow the user to modify the environment (b) and avatar physiological characteristics (c). The OpenSim skeleton can also be loaded and visualized in Unity (d).

DISCUSSION

A software framework for simulating a complete virtual human has been developed and tested. The framework integrates OpenSim, BioGears, and animated anatomy within the Unity gaming engine. Proof-of-concept was demonstrated for using the avatars in mission-relevant simulations.

Preliminary simulations of walking were generated using the task space control framework. Predictive simulations of human movement are currently of great interest in the computational biomechanics community. Several methodologies and associated software tools are available for generating predictive simulations. The OpenSim Moco tool has gained popularity in biomechanics research, but due to its use of direct collocation Moco can only simulate short motions. Reinforcement learning (RL) is another methodology for generating movement simulations. RL can be used to create movement controllers that are robust to disturbances and keep the avatar from falling down, but has the disadvantages of unrealistic movement and lengthy algorithm training times (Schumacher et al., 2023). In the current effort, task space control was selected because it can (in theory) be used to generate simulations of arbitrary duration with parameters (e.g., walking velocity, stride length) that can be adjusted by the user. However, it was found that generating stable walking simulations in OpenSim is nontrivial. Whole-body task space control is an extensive field of study in bipedal robotics, and numerous resources are available for generating stable walking gaits (Fok et al., 2015). In the future, integration of the OpenSim-based task space control with gait generators from bipedal robotics could significantly advance the capability for generating a variety of avatar movements.

Joint torque-driven simulations are substantially faster than muscle-driven simulations due to the fact that joint torques can be solved directly, while muscle forces must be estimated using optimization (Thelen & Anderson, 2006). Due to the computational complexity of muscle-driven simulations, in this work we aimed to use torque-driven simulations. Torque-driven simulations still provide a great deal of biomechanical outputs (e.g., joint torques, ground reaction forces) that can be used to evaluate simulated mission performance. In addition, the outputs of a torque-driven simulation can be used as input for a muscle-driven simulation as a post-processing step if desired. For evaluating mission performance, a key output metric is MEE. In this study, the joint-based MEE plugin tended to overpredict energy expenditure compared to values reported in the literature. This may be due to differences in the gait data relative to the original data used to derive the parameters (Cruz & Yang, 2022). Future efforts should further validate and refine the mathematical models for joint-based MEE estimation to ensure validity across multiple individuals. In addition, further validation is needed for MEE estimates during movements other than walking.

Proof-of-concept was demonstrated for using BioGears to simulate a long-duration ruck march in a high-altitude environment. Validation is also needed for the BioGears predictions in various scenarios. While each individual physiology module within BioGears has been independently validated using experimental data, it remains unclear how accurate the predictions would be for the combined system components.

To make a virtual avatar into a true digital twin of a human, sensor data must be used to continuously update the virtual model. Several potential methods could be used to incorporate sensor data. Inertial measurement units (IMUs) could potentially be used to track movement of the body for use in driving the OpenSim model. However, IMUs are subject to measurement error and drift, which may adversely affect simulation accuracy. Alternative methods could utilize simplified gait metrics (e.g., cadence) with known anthropometric parameters and terrain data from GPS to simulate a "most likely" movement in real-time. For the simulated physiology, a key next step is to incorporate additional sensor data to improve simulation accuracy. Currently, the only input to a BioGears simulation is exercise intensity. Utilizing additional data sources such as heart rate or body temperature in a closed-loop architecture could improve the accuracy of the simulated physiological response.

In summary, all components of the digital human avatars (visual anatomy, physics-based biomechanics, simulated physiology) were integrated into a single framework based on the Unity gaming engine. Although further validation and refinement of the avatars is needed, the software represents a major advance in available tools for integrating fully-featured human avatars into virtual mission planning tools. The ultimate aim of this avatar development effort is to provide a cross-platform, Unity-based avatar asset that can simulate individuals of various anthropometry, sex, and fitness level performing strenuous tasks in various environments. In the future, virtual human avatars can be integrated into existing mission planning or real-time health monitoring applications. Simulations of an entire squad performing a planned mission could provide a "mission performance forecast" to assess individual fatigue levels and the associated impact on mission performance. Real-time physiological data could then be used to monitor actual physiological response and performance during the mission using the forecast as a baseline.

ACKNOWLEDGEMENTS

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CLASSIFICATION: UNCLASSIFIED

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