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# Closeout Memorandum for NRL Base Program 1E42: Predicting Traumatic Brain Injury to the Warfighter Using Uncertainty Propagation

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## **EXECUTIVE SUMMARY**

This document satisfies the closeout requirements for NRL base program 1E42: Predicting Traumatic Brain Injury to the Warfighter Using Uncertainty Propagation. It provides an overview of the technical objectives of the program, technical progress, and dissemination of research findings through publications, reports, and presentations.

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# **CLOSEOUT MEMORANDUM FOR NRL BASE PROGRAM 1E42: PREDICTING TRAUMATIC BRAIN INJURY TO THE WARFIGHTER USING UNCERTAINTY PROPAGATION**

## **1. PROGRAM DESCRIPTION**

The objective of this program is to establish population and scenario-based prediction of traumatic brain injury (TBI) to the warfighter from explosive blast insult by accounting for variations in blast profile and orientation, biological constitutive behavior, and subject-specific anatomy. This work is focused on advancing key computational simulation techniques to enable characterization and propagation of input uncertainty in order to determine a probabilistic description of the mechanical response of the brain as well as identify important input and output quantities. Progress has been made in the following areas: 1) Monte Carlo simulation propagating geometric uncertainty through to mechanical response uncertainty 2) Code development and implementation for reduced order model construction, and 3) Bayesian model class and model parameter optimization for biological soft tissue material characterization. More detailed description of these topics are given below.

### **1.1 Monte Carlo simulation propagating geometric uncertainty through to mechanical response uncertainty**

A stochastic description and simulation algorithm for morphology variation of the human head has been developed. The objective of this task was to develop a model that can accurately describe the variation in geometry of the human head using as few parameters as possible. This can be treated as input uncertainty, which can be sampled for Monte Carlo simulation of finite element models to quantify the uncertainty of TBI prediction due to geometric variation. The head morphology model was based on approximately 200 3-D MRI scans of human heads, which have been acquired from the International Consortium of Brain Mapping, an online resource. Image segmentation using the Brainsuite software was applied such that brain and head masks were created and a template model was warped (or mapped) to each subject. The template was a previously segmented 3-D MRI scan of a 50th percentile Caucasian male. The warping model chosen is an affine transformation because of its simplicity and accuracy. Following the development of a stochastic model for head geometry, the process of fully automating and executing the MC simulation of blast-induced TBI has been completed. The process entails warping a surface mesh representation of the template model to a subject, creating an FE mesh of the subject, and executing the FE simulation. The FE mesh is created in software Simpleware FE (Synopsis, Mountain View, CA) through its python script interface. The FE software CoBi is used to run the blast-induced TBI simulations. The FE code has been benchmarked through a number of verification and mesh convergence studies. A hyper-viscoelastic constitutive law was implemented in CoBi represented by an Ogden model for the hyperelasticity and a Prony series representing the shear modulus for the viscoelasticity. The results of the MC simulation show that head geometry variation causes variation in the magnitude of the mechanical response. The same anatomical regions can receive significantly different mechanical response due to head geometry. However, it was observed that the extreme values of mechanical response quantities are located in the same regions for all subjects.

## 1.2 Code development and implementation for reduced order model construction

Progress has been made in code development, implementation, and initial execution of a reduced order model (ROM) for blast-induced TBI simulation. The software AERO-S was chosen for this task because of its existing ROM capabilities. Numerous enhancements were necessary for the application of interest and are listed as follows. A hyper-viscoelastic constitutive model was implemented. This model entails an Ogden model for hyperelasticity and a Prony series model for the shear modulus for viscoelasticity. A custom-developed mesh and geometry definition data transfer technology to port ABAQUS geometry files to AERO geometry files has been developed in order to facilitate the automation of mesh generation. The translator has the capability to cover nodes, element connectivity, element sets and parts. Attention has been paid to transfer boundary and part definitions from ABAQUS to AERO-S, such that multi-material systems can be properly defined. In coordination with AERO-S developers, the off-line/on-line hyper-reduced order methodology was implemented. The off-line component refers to executing the high dimensional model to identify the reduced order representation and it includes sampling algorithms for the parameter space and a suite of procedures to identify the reduced bases. This mainly includes collection of the mechanical response of the high-fidelity model and performing singular value decomposition. The on-line component of ROM construction refers to the process of using the reduced order bases to execute the reduced order model for a specific desired parameterization. The specific steps within this process are (1) mass-orthonormalization, (2) sampling the mesh via the so-called energy conserving sampling and weighting (ECSW) process, (3) execution of the ROM using an explicit algorithm, and (4) projection of the ROM back to the high dimensional space for post-processing. This approach was exercised for blast-impacted human head assemblies. The hyper-reduction model was found to perform 200x faster than the high-fidelity model without much loss in accuracy. This improvement in efficiency is necessary for the purpose of sampling the uncertainty of the parameters associated with the physics of the problem.

## 1.3 Bayesian model class and model parameter optimization for biological soft tissue material characterization

Considerable time was spent compiling the past efforts of NRL on constitutive modeling of biological soft materials. There is a great deal of legacy work on constitutive modeling of biomaterials, so these various efforts over the years were condensed into a single report detailing the relevant mechanics theory, constitutive modeling approach, parameter estimation procedure, and component-specific results for all of the biomaterials included in the finite element (FE) model of the human head. The compilation of the report spawned a broader study on the constitutive modeling and parameter estimation of the various biomaterials. A deterministic optimization scheme was replaced by a Bayesian inference-driven approach to uncertainty quantification. For implementation of the Bayesian analysis, both the Hamiltonian Monte Carlo (HMC) and the Nested Sampling algorithms were used as the random vector simulation engine.

Through the use of these algorithms, a Bayesian model calibration framework was developed in order to determine the posterior parameter distributions of a hyperviscoelastic constitutive model using mechanical testing data of brain tissue. It was shown that through Bayesian calibration, the capability of an experimental design to identify parameter values can be quantitatively evaluated. A large range of experimental designs (i.e., loading modes) were considered, including rate dependent, cyclic loading through compression, shear, and tension, as well as shear and compression relaxation loading. The joint probability distribution of the parameters enabled assessment of parameter sensitivity, uncertainty, correlation, and model calibration error as a function of experimental design. By calibrating simultaneously to numerous combinations of loading modes, redundancy in loading mode as well as parameter convergence can be evaluated based on model

calibration error and parameter variability. The results of this study verified that the inclusion of more loading modes in the calibration increases the accuracy of parameter identification, while only one or two loading modes may provide almost no information for identifying certain parameters.

## **2. DISSEMINATION**

### **2.1 Peer reviewed journal publications**

1. Wonmo Kang, Michael C. Robitaille, Marriner Merrill, Kirubel Teferra, Chunghwan Kim, and Marc P. Raphael. Mechanisms of cell damage due to mechanical impact: an in vitro investigation. *Scientific reports*, 10(1):1–12, 2020
2. Kirubel Teferra and Patrick T Brewick. A bayesian model calibration framework to evaluate brain tissue characterization experiments. *Computer Methods in Applied Mechanics and Engineering*, 357:112604, 2019
3. Kirubel Teferra, X Gary Tan, Athanasios Iliopoulos, John Michopoulos, and Siddiq Qidwai. Effect of human head morphological variability on the mechanical response of blast overpressure loading. *International journal for numerical methods in biomedical engineering*, 34(9), 2018
4. Patrick T Brewick and Kirubel Teferra. Uncertainty quantification for constitutive model calibration of brain tissue. *Journal of the Mechanical Behavior of Biomedical Materials*, 85:237-255, 2018

### **2.2 Refereed conference papers**

1. Athanasios P. Iliopoulos, John G. Michopoulos, Philip Avery, Charbel Farhat, Kirubel Teferra, Siddiq Qidwai. Towards Model Order Reduction for Uncertainty Propagation in Blast-induced Traumatic Brain Injury. *Proceedings of the ASME 2017 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2017*, August 6-9, 2017, Cleveland, OH, USA, paper IDETC/CIE2017-67556
2. Patrick Brewick and Kirubel Teferra. Addressing uncertainty in constitutive model forms and parameters for FE models of the human head subjected to blast loading. *In the ASME International Mechanical Engineering Congress and Exposition (IMECE)*, Tampa, FL, November 3-9 2017

### **2.3 NRL Formal reports**

1. Patrick Brewick, Robert Saunders, and Amit Bagchi. *Biomechanical Modeling of the Human Head*. NRL Technical Report, 2017

### **2.4 Conference presentations**

1. Patrick Brewick and Kirubel Teferra. Bayesian calibration for models with nonlinear inequality parameter constraints. *In the SIAM Conference on Uncertainty Quantification*, Garden Grove, CA, April 16-19 2018

2. Patrick Brewick and Kirubel Teferra. Investigating the uncertainty in constitutive model calibration for the hyperelastic behavior of brain tissue. In the 16th European Mechanics of Materials Conference (EMMC16), Nantes, France, March 26-28 2018
3. Kirubel Teferra, X. Gary Tan, Athanasios Iliopoulos, John Michopoulos, and Siddiq Qidwai. Modeling the effect of head shape on traumatic brain injury prediction due to blast loading. In the ASME International Mechanical Engineering Congress and Exposition (IMECE), Tampa, FL, November 3-9 2017
4. Patrick Brewick and Kirubel Teferra. Investigating uncertainty in constitutive modeling of components of the human head (poster). In the 41st Annual Meeting of the American Society of Biomechanics, Boulder, CO, August 8-11 2017