Optimizing the Biofidelity of the Warrior Injury Assessment Manikin through Design of Experiments

M.P. Boyle[1], A.M. Lennon[1], N.A. Vavalle[1], M.T. Shanaman[1], C.W. Lomicka[1], C.O. Pyles[1], J.P. Schap[2], A.M. Baker[2], F.S. Gayzik[2], M.R. Chowdhury[3], R.S. Armiger[1]

[1] The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723

[2] Wake Forest University Center for Injury Biomechanics, Winston-Salem, NC 27101

[3] Army Research Laboratory, Adelphi, MD 20783

Abstract

With improvised explosive devices beneath military vehicles causing an increasing number of casualties amongst warfighters, the United States Army requires a method by which to evaluate injury mitigation technologies in vehicles, including seat designs and other safety systems. In response to complications associated with the use of Post Mortem Human Subjects (PMHS), the United States Army Research Laboratory initiated an endeavor to develop a biofidelic Anthropomorphic Test Device (ATD), to serve as a surrogate for injury prediction in underbody blast (UBB) tests with military vehicles. Accurately predicting injuries, with the aptly named Warrior Injury Assessment Manikin (WIAMan), began with the development of an ATD with high biofidelity, or specifically, the ability to reproduce the response of the human body to an UBB event. The WIAMan design process leveraged the modeling and simulation of the whole body ATD in LS-DYNA®, a 2.3M element model with over 50 different materials. The WIAMan LS-DYNA model helped to identify and avert strength of design issues as well as to guide design changes with regards to desired dynamic responses, technically referred to as Biofidelity Response Corridors (BRC). BRCs are established through PMHS studies in UBB simulators as a way to define the range of expected responses from PMHS for a specific input condition. The design options for maximizing the correlation between simulations and BRCs across three UBB test conditions primarily included variations in materials and geometries. However, the myriad of design parameter combinations, together with multiple interdependencies between outcome variables, made optimizing the design a challenge. Selecting seven readily modified design parameters, and reasonable variations within those parameters, helped to bound the problem. Next, a statistical design of experiments was executed, using SAS JMP® software that specified 57 whole body LS-DYNA simulations. Through the use of modeling tools in JMP®, the simulation results produced optimized values for the seven parameters that maximized correlation between dynamic responses of the WIAMan model and the BRCs.

Introduction

The U.S. Department of Defense (DOD), and the U.S. Army in particular, need a warrior-representative (human-like or biofidelic) anthropomorphic test device (ATD) to replace the currently used Hybrid III ATD fleet for effective evaluation and assessment of Soldier survivability in ground vehicles subjected to under-body blast (UBB) threats. The Hybrid III ATD, currently used for Warfighter survivability and protection evaluation, is not scientifically valid for the UBB environment. It lacks a representative human-like response and is inadequate for determining the risk of skeletal injury due to vertical accelerative loading (Bailey et al. 2015; Scherer et al. 2010). The capability to accurately predict vehicle-mounted occupant responses caused by UBB loading and provide an operationally relevant Soldier surrogate is critical to contributing to vehicle system designs and improvements in Warfighter survivability, as well as advancing the state of the art in UBB injury assessment. The ATD being developed specific to the UBB environment is the Warrior Injury Assessment Manikin (WIAMan), under the purview of the U.S. Army Research Laboratory (Chowdhury 2017).

Designing an ATD to meet these challenges involved an interdisciplinary team, including post-mortem human subject (PMHS) testing experts to establish target ATD responses and ATD testing experts who compared the ATD response to PMHS defined targets. The team also included modeling and simulation (M&S) experts to help guide the design toward the best possible correlation between PMHS and ATD responses and provide a complementary finite element model of the physical ATD for studying UBB independently.

Methods

WIAMan M&S started with a 3-D computer-aided design (CAD) geometry of a concept 50th percentile male ATD (Humanetics® 2014, Reed 2013; Reed and Ebert 2014) provided by the government. A significant M&S effort resulted in a high quality mesh that represented most of the design's approximately 1600 individual parts. High strain rate testing of polymeric materials served as the basis for several material models, leveraging Berstrom-Boyce, Ogden, and Blatz-Ko, all optimized through the use of LS-OPT® or MCalibration® (Veryst Engineering®, Needham Heights, MA). The LS-DYNA model, shown in Figure 1, consists of 2.3 million elements and 1.9 million nodes and represents a mass of 79.7 kg.

The seat and floor that transfer the impact loads into the WIAMan, representing the Applied Physics Laboratory's (APL) Vertically Accelerated Load Transfer System (VALTS) shown in Figure 2, account for another 1.3 million elements. Utilizing 40 CPUs, the runtime for a 100 ms simulation measured about 68 hours.

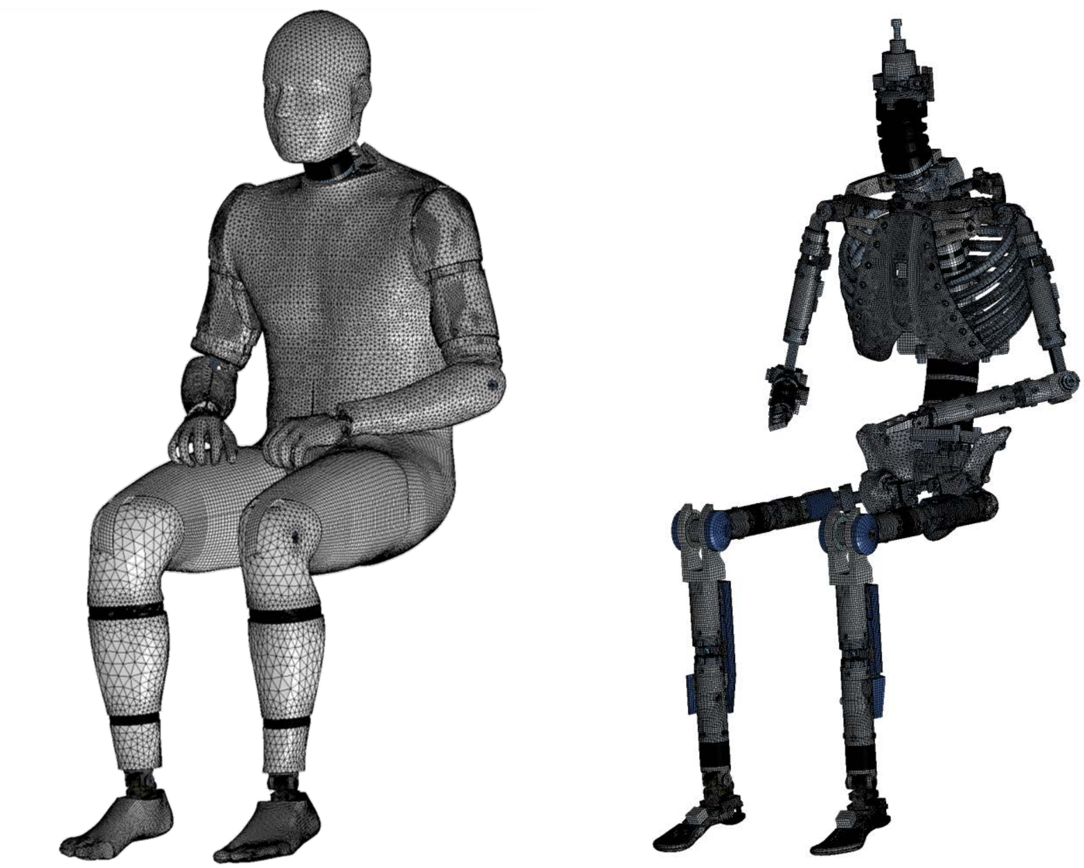


Figure 1: The WIAMan whole body, LS-DYNA, finite element model, with and without flesh.

Figure 2: The WIAMan whole body, LS-DYNA, finite element model, with personal protective equipment and seated in VALTS.

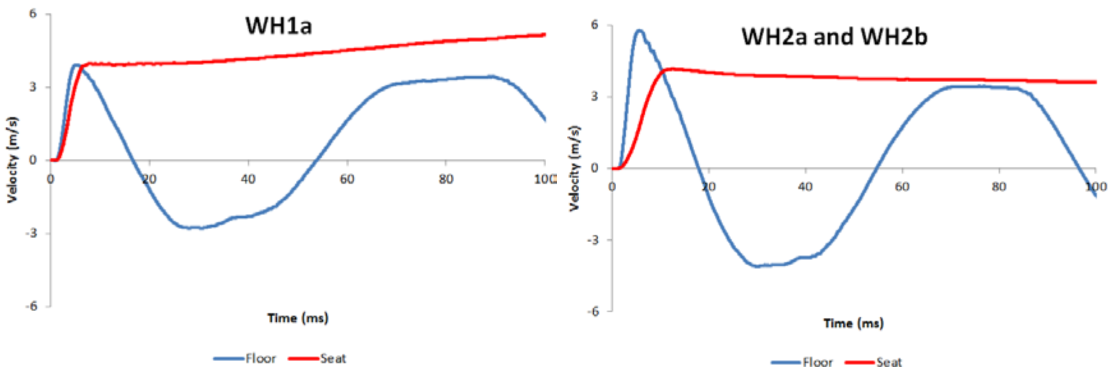


Figure 3: Prescribed velocities of the VALTS floor and seat for three moderate loading conditions, WH1a, WH2a, and WH2b.

In approximately replicating the reactions of a vehicle's floor and seat accelerated by an UBB, the floor and seat velocities of VALTS are specifically, accurately, and independently prescribed by the curves depicted in Figure 3. The WIAMan design ideally maximizes the correlation between PMHS and ATD responses, known as Biofidelity Parameters (BP), across three different (moderate) loading conditions, known as WH1a, WH2a, and WH2b, with the latter one including a representation of personal protective equipment (PPE):

- WH1a: Floor velocity peaking at 4 m/s in 5ms and seat velocity peaking at 4 m/s in 5 ms, boots only
- WH2a: Floor velocity peaking at 6 m/s in 5ms and seat velocity peaking at 4 m/s in 5 ms, boots only
- WH2b: Floor velocity peaking at 6 m/s in 5ms and seat velocity peaking at 4 m/s in 5 ms, full PPE

The WIAMan LS-DYNA model outputs data from numeric load cells, accelerometers, and rotational rate sensors, equivalent to those found in physical ATD, and relevant for comparison to observed PMHS responses. Biofidelity Response Corridors (BRC) define the acceptable range of variability from the ideal BP curve. Comparison of ATD responses to BRCs occurs through an objective rating system called CORrelation and Analysis (CORA) (Gehre and Gades 2009). CORA provides a weighted average score of the size, shape, and phase components combined with an assessment of fit within a set of corridors and ranges from 0 (worst) to 1 (best). The four components of CORA have been shown to provide independent contributions to the overall score (Vavalle 2013). In the absence of an ATD to test, M&S provided predicted responses for rating iterations of the ATD design and made comparisons directly to the BRC data. Thirty-seven CORA scores weighted according to the likelihood of their contribution to an injury, aggregate into an overall CORA score for that design iteration for that particular loading condition. The three aggregate CORA scores, one each for WH1a, WH2a, and WH2b, average into an overall CORA score. The program ambitiously targeted an average overall CORA score of at least 0.65. Starting with an overall CORA score of 0.62, the program achieves its goal with an increase of 0.03 but generally sought to maximize the overall CORA score. Table 1 lists BPs, CORA scores from ATD physical testing for the WH1a loading condition, and their corresponding weighting factors in calculating the aggregate CORA scores. The overall CORA score of the LS-DYNA model of the baseline design with respect to BRCs measured 0.55. Setting aside the inequality between the overall physical ATD CORA score and the overall LS-DYNA model CORA score, ideally, the optimization reveals a specific combination of parameters that result in an increase to the overall LS-DYNA model CORA score of 0.03 or better, that when applied to the physical ATD, results in a comparable change.

Biofidelity Parameter (BP)	Physical ATD BP CORA Score	BP Weight Factor
BP-01X Head Accel X	0.742	2
BP-01Y Head Accel Y	0.405	0
BP-01Z Head Accel Z	0.465	4
BP-02 Head Accel Resultant	0.464	0
BP-03X Head Rotation X	0.547	0
BP-03Y Head Rotaion Y	0.861	8
BP-03Z Head Rotation Z	0.505	0
BP-04X Motion of Head X	0.465	8
BP-04Z Motion of Head Z	0.495	8
BP-05 Head Rotation relative to torso	0.708	4
BP-06 Head Rotation relative to pelvis	0.915	0
BP-18X T1 Spinal Accel X	0.756	4
BP-18Z T1 Spinal Accel Z	0.702	8
BP-19 T1 Spinal Rotation Y	0.404	6
BP-24X T12 Spinal Accel X	0.549	8
BP-24Z T12 Spinal Accel Z	0.611	8
BP-25 T12 Spinal Rotation Y	0.676	6
BP-42X Pelvis Accel X	0.799	8
BP-42Y Pelvis Accel Y	0.755	0
BP-42Z Pelvis Accel Z	0.793	8
BP-43 Pelvis Accel Resultant	0.724	0
BP-44X Pelvis Rotation X	0.512	0
BP-44Y Pelvis Rotation Y	0.836	6
BP-44Z Pelvis Rotation Z	0.673	0
BP-47X Distal Femur Accel X	0.287	6
BP-47Z Distal Femur Accel Z	0.534	4
BP-49X Motion of Knee X	0.758	2
BP-49Y Motion of Knee Y	0.636	6
BP-49Z Motion of Knee Z	0.361	6
BP-50X Tibal Accel X	0.571	2
BP-50Z Tibia Accel Z	0.884	10
BP-53 Foot Accel Z	0.537	8
BP-54X Motion of feet X	0.644	2
BP-54Y Rotation of feet Y	0.580	6
BP-54Z Motion of feet Z	0.299	6
BP-67 Distal Femur Rotation Y	0.605	4
BP-68 Distal Tibia Rotation Y	0.537	2

Table 1: Biofidelity Parameters CORA scores from ATD physical testing, and their weighting factors in calculating the aggregate CORA score. WH1a scores only. Directions per SAE J211.

Optimization

Throughout the design process, attempts to improve individual CORA scores through targeted design changes included varying flesh thicknesses and stiffnesses, lumbar spine material stiffness, cervical spine geometry, abdomen geometry and material stiffness, tibia compliant element stiffness, including a compliant element in the femur or not, including a plug in the heel or not, further sculpting of the foot flesh, and more. Inevitably, the gain in any one score became offset by declines in others. With the interdependency of design changes on CORA scores apparent, the best chance for maximizing the overall CORA score could only occur through an optimization at the system level. This could most readily be achieved through FEA; manufacturing parts for design changes would be costly, but implementing them in the computational realm was cheap. However, with the number of design variations infinite, the problem needed bounding. Table 2 lists the seven readily modifiable design parameters chosen for the basis of a whole body optimization and their ranges as a percent difference with respect to the nominal stiffness or thickness. Scaling the stiffness is achieved by scaling the stress of the stress-strain curves of every strain rate used in defining a material, resulting in a new material model. The foot flesh plug is a replacement of the portion of the foot flesh, at the heel, with a separate, stiffer material.

Parameter	**Range**	
	Minimum (% w/r/t Nominal)	**Maximum (% w/r/t Nominal)**
Pelvis Flesh Stiffness	75	125
Pelvis Flesh Thickness	50	100
Lumbar Spine Stiffness	50	100
Tibia Compliant Element Stiffness	75	125
Foot Flesh Stiffness	75	125
Abdomen Stiffness	75	125
Foot Flesh Plug	Not Included	Included

Table 2: Variables and their ranges for the WIAMan whole body design optimization.

Design of Experiments (DoE) is a structured, organized way of conducting a series of tests so that appropriate data can be analyzed by statistical methods, resulting in valid and objective conclusions. The application of DoE to the WIAMan whole body finite element analysis (FEA) allows for an efficient parameter space investigation, reducing what would otherwise be 4374 simulations to a more practical number. Using the parameters from Table 2, a statistical design of experiments was executed, using SAS JMP® software (SAS Campus Drive, Cary, NC) that specified 57 whole body simulations, listed in Table 3. The DoE output predictive statistical models for any combination of the seven parameters included individual BP CORA scores, aggregate CORA scores for each of the three loading conditions, and an overall average CORA score. Through the use of the predictive modeling tools in JMP®, the simulation results produced optimized values for the seven parameters that maximized correlation between dynamic responses of the WIAMan model and the BRCs.

Run #	Pelvis Flesh Stiffness	Pelvis Flesh Thickness	Lumbar Spine Stiffness	Tibia Compliant Element	Foot Flesh Stiffness	Abdomen Stiffness	Environment	Foot Flesh Plug
1	100	50	100	100	100	125	WH2a	Without
2	100	50	75	75	125	125	WH2b	With
3	125	50	50	100	125	100	WH2b	Without
4	125	50	50	75	100	125	WH2a	With
5	125	100	50	75	125	125	WH1a	Without
6	125	50	50	125	125	75	WH1a	With
7	125	50	75	125	75	100	WH2a	With
8	125	75	100	125	125	75	WH2b	Without
9	125	50	100	125	125	125	WH1a	Without
10	75	50	75	100	75	125	WH2b	Without
11	125	100	100	125	100	100	WH1a	With
12	75	100	100	100	125	125	WH2b	With
13	100	100	100	75	125	75	WH1a	Without
14	75	100	50	125	75	125	WH2a	With
15	125	100	50	75	75	125	WH2b	With
16	75	75	75	125	100	100	WH2b	With
17	75	75	100	75	75	75	WH2a	With
18	75	100	75	125	75	75	WH1a	With
19	75	50	50	100	125	75	WH2a	With
20	75	100	50	75	125	100	WH1a	With
21	75	50	50	100	75	100	WH1a	With
22	125	50	75	75	75	75	WH2b	With
23	100	100	100	75	75	100	WH2b	With
24	125	50	50	125	75	125	WH1a	Without
25	125	100	50	125	100	75	WH2a	Without
26	125	75	100	75	100	125	WH2b	Without
27	125	75	50	125	125	125	WH2a	With
28	125	50	100	75	75	125	WH1a	With
29	75	75	50	100	125	75	WH1a	Without
30	125	100	50	125	75	75	WH2b	With
31	100	75	75	100	100	125	WH1a	With
32	125	100	75	100	125	75	WH2b	With
33	75	100	50	75	100	75	WH2b	Without
34	75	50	50	125	75	75	WH2a	Without
35	100	100	50	125	125	125	WH2b	Without
36	125	50	75	75	125	75	WH2a	Without
37	125	50	100	100	75	75	WH1a	Without
38	125	100	100	75	75	75	WH2a	Without
39	100	100	75	75	100	125	WH2a	With
40	75	50	100	125	125	125	WH2a	With
41	125	100	50	75	75	75	WH2a	With
42	75	75	50	75	125	125	WH2a	Without
43	100	75	50	100	100	100	WH2b	With
44	100	75	50	75	75	100	WH2a	Without
45	75	50	100	100	125	75	WH1a	With
46	125	100	100	125	75	125	WH2a	Without
47	100	100	75	100	75	100	WH2b	Without
48	75	100	75	100	125	100	WH2a	Without
49	100	100	100	125	100	75	WH2a	With
50	125	75	100	75	125	100	WH2a	With
51	125	50	100	125	100	125	WH2b	With
52	125	75	75	75	100	75	WH1a	With
53	75	50	75	75	100	100	WH1a	Without
54	75	75	100	125	75	125	WH1a	Without
55	100	75	75	100	100	100	WH1a	Without
56	75	50	100	100	125	75	WH2b	Without
57	75	100	50	75	75	125	WH1a	Without

Table 3: Simulations (57) prescribed by the statistical DoE.

Results

The 57 DoE simulations required over 140k CPU hours of simulation time. The optimized parameters ultimately raised the overall CORA score by 0.015, from 0.553 to 0.568. As shown in Figure 4, decreases in certain CORA scores offset the gains made in others. Table 4 lists the optimal values for each of the seven optimization parameters.

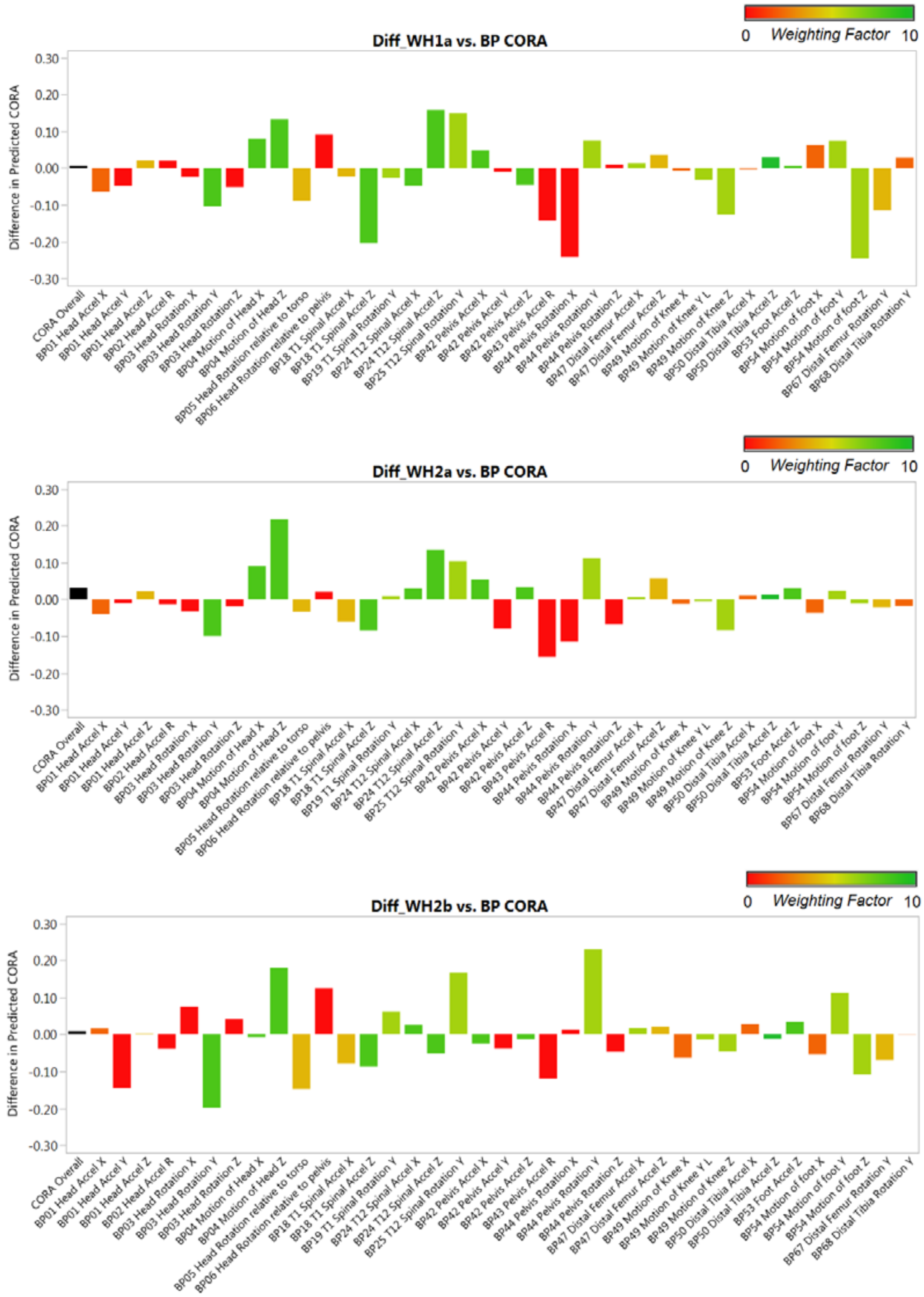


Figure 4: Predicted differences in individual BP CORA scores, for WH1a, WH2a, and WH2b respectively, between the nominal WIAMan design finite element model (FEM) and the optimized design.

Parameter and Range	Optimal Value (% w/r/t Nominal)
Pelvis Flesh Stiffness (75-125%)	125
Pelvis Flesh Thickness (50-100%)	50
Lumbar Spine Stiffness (50-100%)	100
Tibia Compliant Element Stiffness (75-125%)	75
Foot Flesh Stiffness (75-125%)	125
Abdomen Stiffness (75-125%)	100
Foot Flesh Plug (Included or Not)	Included

Table 4: Values of parameters that maximize the overall CORA score for the WIAMan whole body.

The optimal parameter values output from a DoE study may fall anywhere within their allowed range. However, of the six continuous variables (foot flesh plug is a 2-factor categorical variable), five landed at the extents of their range. Only the abdomen stiffness ended up within its range, coincidentally at the nominal stiffness. Whole body simulations using the optimal values revealed reasons for CORA score differences predicted by the DoE. A sample of BP responses, for both the nominal, baseline design and optimized design (referred to as "Golden Parameters" in the plots), are shown in Figure 6. The mean CORA scores and the ranges of the CORA scores for individual BPs, shown in Figure 5, highlights the possibility of drastically improving any one score. The ranges in Figure 5 depict only the results from 57 DoE specified simulations, setting aside the predictive capability of the DoE statistical model. The extent of the ranges highlights the potential for drastically improving any one CORA score, however, as previously noted, net gains in the overall CORA score were relatively minor in considering the system level response.

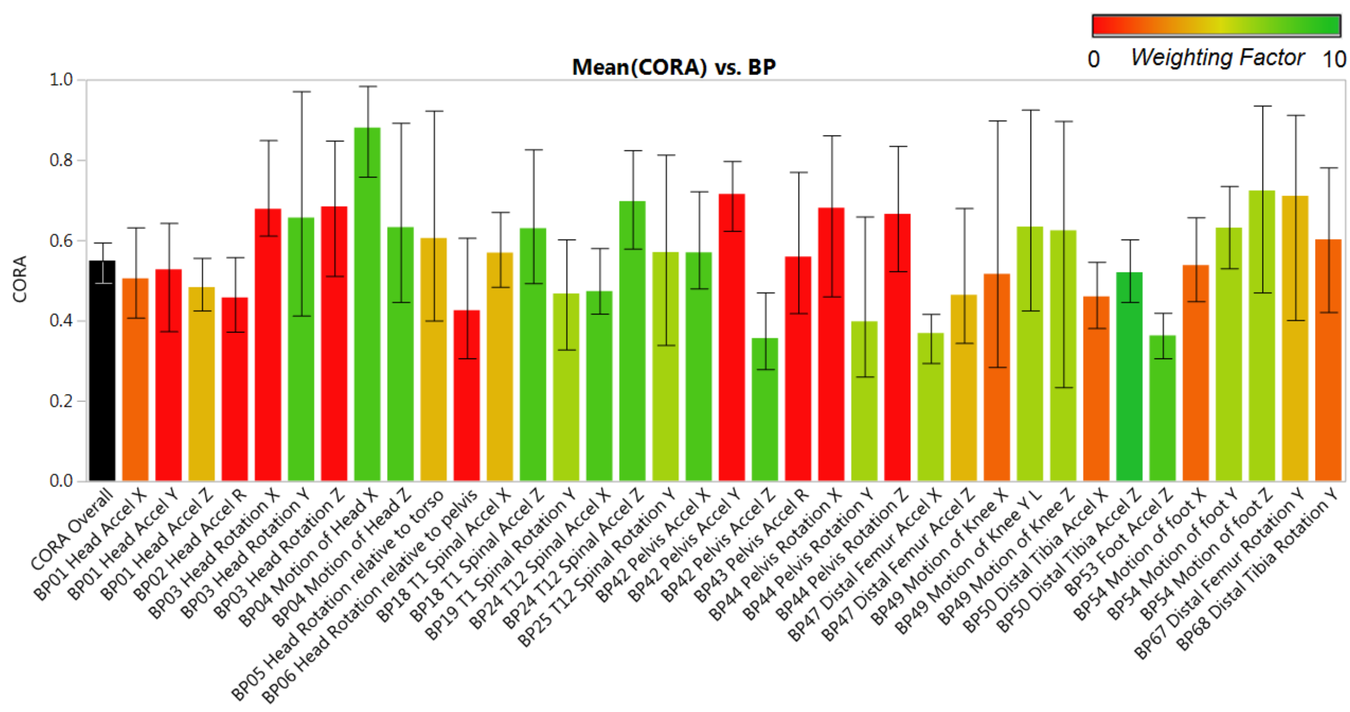
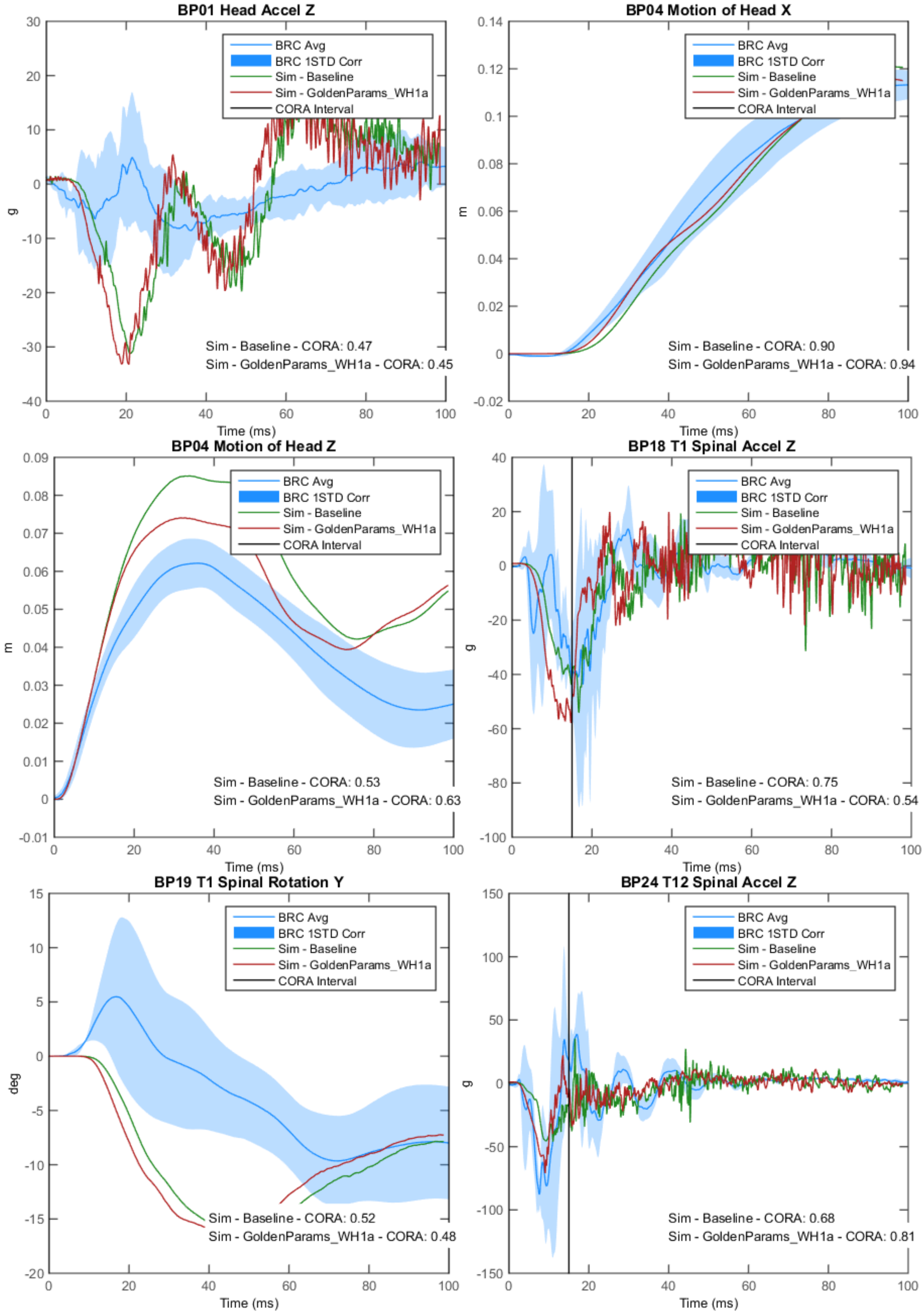


Figure 5: Average BP CORA scores, for only the 57 simulations required for the DoE analysis, across all three loading conditions. The error bars depict deviation in scores.


BP01 Head Accel Z
BRC Avg
BRC 1STD Corr
Sim - Baseline
Sim - GoldenParams_WH1a
CORA Interval
Sim - Baseline - CORA: 0.47
Sim - GoldenParams_WH1a - CORA: 0.45
g
Time (ms)
BP04 Motion of Head X
Sim - Baseline - CORA: 0.90
Sim - GoldenParams_WH1a - CORA: 0.94
m
Time (ms)
BP04 Motion of Head Z
Sim - Baseline - CORA: 0.53
Sim - GoldenParams_WH1a - CORA: 0.63
m
Time (ms)
BP18 T1 Spinal Accel Z
Sim - Baseline - CORA: 0.75
Sim - GoldenParams_WH1a - CORA: 0.54
g
Time (ms)
BP19 T1 Spinal Rotation Y
Sim - Baseline - CORA: 0.52
Sim - GoldenParams_WH1a - CORA: 0.48
deg
Time (ms)
BP24 T12 Spinal Accel Z
Sim - Baseline - CORA: 0.68
Sim - GoldenParams_WH1a - CORA: 0.81
g
Time (ms)

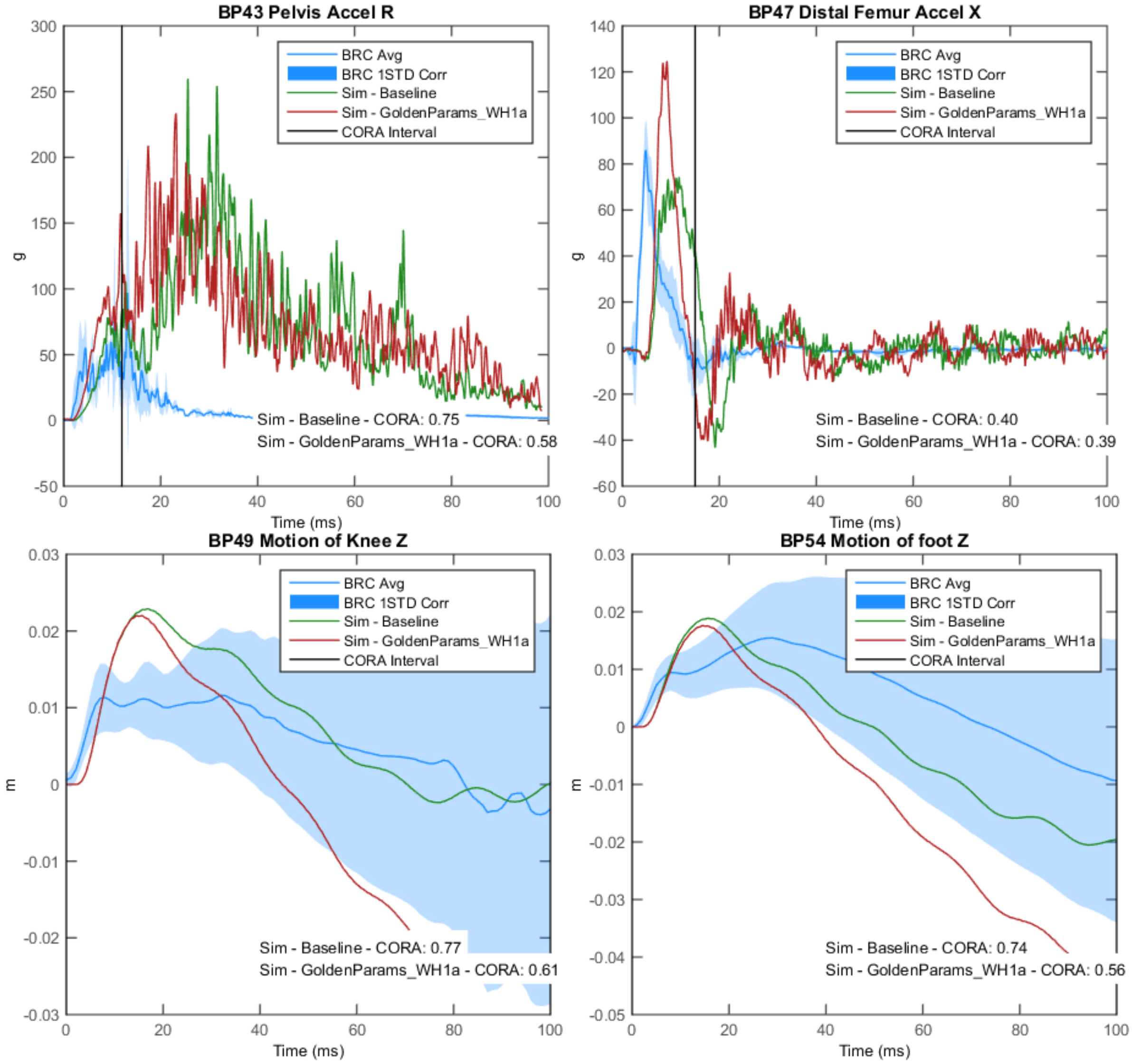


Figure 6: Sample of BP responses for WH1a input condition, highlighting those with the greatest difference in CORA scores between the baseline and optimal (GoldenParams) models and those with the greatest opportunity for improvement. The solid blue line represents the average response from PHMS testing, the light blue band is the one standard deviation corridor.

Conclusions

Ironically, the interdependency of responses, the rationale for performing the DoE optimization originally, became the roadblock to realizing a dramatic improvement in correlation. However, there are a number of positive takeaways from the DoE optimization, despite not having realized a massive increase in the overall CORA score. First and foremost, the DoE optimization revealed the futility, at the system level, of attempting to individually improve BP CORA scores by stepwise changes to individual components, sparing the program expensive trial-and-error cycles of manufacturing potential designs. Additionally, if design changes are required for other reasons, like durability, flexibility, manufacturability, etc., those can be made with reasonable assurance that the overall CORA score will remain largely unchanged.

References

Bailey AM, Christophe, JJ, Salzar, RS, Brozoski F. Comparison of Hybrid-III and postmortem human surrogate response to simulated underbody blast loading. J Biomech Eng. 2015;137:051009.

Chowdhury MR, Vavalle NA, Pyles CO, Shanaman MT, Lomicka CW, Boyle MP, Armiger RS, Baker AM, Schap JP, Gayzik FS, Bell C, Nochetto H, Kiessling G, Lister K, Baltis T, Robeck C, and Yow C. Warrior Injury Assessment Manikin (WIAMan) Anthropomorphic Test Device (ATD) Tech Demonstrator Finite-Element Models Development. 2017. ARL Technical Report.

Gehre C, Gades H. Objective rating of signals using test and simulation responses. 21st enhanced safety of vehicles. Stuttgart, Germany, 2009.

Humanetics® Innovative Solutions. (2014). Warrior Injury Assessment Manikin 3D CAD Geometry of a Concept 50th Percentile Male ATD. Farmington Hills, MI.

Reed MP. Development of anthropometric specifications for the warrior injury assessment manikin (WIAMan). University of Michigan Transportation Research Institute. 2013. Technical Report No.: UMTRI-2013-38. https://deepblue.lib.umich.edu/bitstream/handle/2027.42/112058 /103198.pdf?sequence=1&isAllowed=y.

Reed MP, Ebert SM. The seated soldier study: posture and body shape in vehicle seats. DTIC document. Ann Arbor (MI): Michigan University, Transportation Research Inst; 2013 Oct 31 [accessed 2014]. http://www.dtic.mil/docs/citations/ADA623016.

Scherer RD, Felczak C, Halstead S. Vehicle and crash-dummy response to an underbelly blast event. 54th Stapp Conference Proceedings (Presentation Only). 2010 Nov 3–5, Scottsdale, AZ. https://blastinjuryresearch.amedd.army.mil/docs/ubb/Vehicle_and_Crash_Dummy_response_to_an_underbelly_blast_event.pdf.

SAE J211 – Instrumentation for Impact Tests. Available from Society of Automotive Engineering (SAE) International, Commonwealth Drive, Warrendale, PA 15096 0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

Vavalle, N. A., Jelen, B. C., Moreno, D. P., Stitzel, J. D., & Gayzik, F. S. (2013). An Evaluation of Objective Rating Methods for Full-Body Finite Element Model Comparison to PMHS Tests. Traffic Injury Prevention, 14(SUPPL1). https://doi.org/10.1080/15389588.2013.802777