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EFFECTS OF OCCUPANT SIZE, MILITARY GEAR, SEATBELT TYPE, AND ADVANCED SEATBELT FEATURES ON OCCUPANT KINEMATICS IN TACTICAL VEHICLES DURING FRONTAL CRASHES

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ABSTRACT

The objective of this study is to understand the occupant kinematics and injury risks in a light tactical vehicle under frontal crash conditions using a combination of physical tests and computer simulations. A total of 20 sled tests were conducted in a representative environment to understand occupant kinematics, and quantify the effects from occupant body size (5th/50th/95th), military gear (helmet/vest/varying gear configurations), seatbelt type (5point/3point), and advanced seatbelt features (pre-tensioner/load limiter) on occupant kinematics and injury risks in frontal crashes. These tests have been used to validate a set of finite element (FE) models of occupants, gear, and restraints. Kinematics exhibited often included submarining due to the lack of knee bolster and the added weight from the military gear. Body size, seatbelt type, and advanced belt features also showed significant effects on occupant kinematics.

INTRODUCTION

Advanced restraint technologies, such as seatbelt pre-tensioners, load limiters, and airbags, have the potential to provide improved occupant protection in crashes, but they are currently not utilized in military vehicles. Optimally implementing these technologies requires a better understanding of the occupant kinematics and injury risks in crash scenarios with military vehicles. The solutions are not necessarily the same as those used in passenger vehicles because of differences in crash involvement, occupant characteristics, vehicle compartment geometry, and occupant seating posture. Military gear may also affect restraint system interaction and injury risk. Experimental data and computational models for quantifying occupant impact responses and injury risks in military vehicles are largely lacking. The limited research available regarding the influence of personal protection equipment is mainly focused on lower extremity protection in landmine blasts (Harris et al. 1999) and head protection in blast-wave situations (Grujicic et al. 2011). Therefore, the impact of military gear on whole body injury during frontal impacts is entirely unknown. Additionally, although the influence of advanced restraint systems on civilian occupant kinematics and injury outcomes has been extensively studied (Forman et al. 2009; Hu et al. 2015; Newberry et al. 2006), the influence of military gear on seatbelt interactions is limited. Therefore, the objective of this study is to understand the occupant kinematics and injury risks in a representative light tactical vehicle environment under frontal crash conditions using a combination of physical tests and computer simulations.

METHODS

An overview of the methods being used during the entire study is shown in Figure 1, which include two series of sled tests, computational model development and validation, baseline full vehicle crash test, parametric simulations, design optimizations, and final full vehicle crash test. Since this is an on-going project, in this paper we are only presenting the results for sled tests without airbag use, and model development and validation against those sled tests.

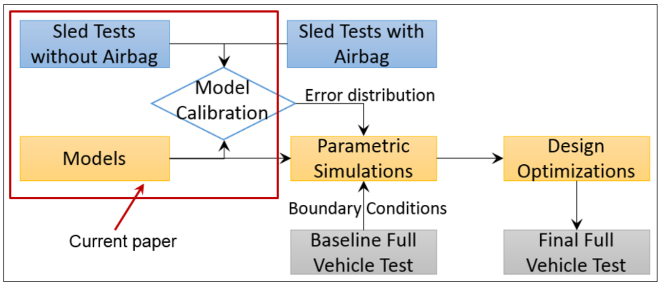


Figure 1: Method overview for the entire project

Sled Tests

A total of twenty frontal-impact sled tests were conducted using a custom-built sled buck which was constructed from 3D scans of a Hummer H1 vehicle (Figure 2). The buck was reconfigurable to represent both the driver and passenger compartments. All the tests were performed in a frontal crash configuration with a 30 mph delta-V and a peak acceleration of 25 g (Figure 2).

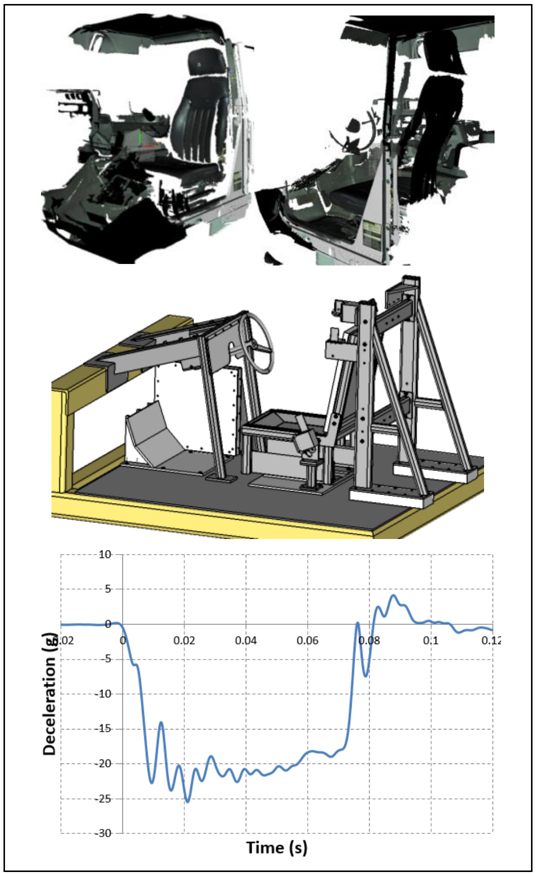


Figure 2: 3D scan of a Hummer H1 (top), custom-built frontal impact test buck (middle), and sled crash pulse (bottom).

The tests in this study used the Hybrid III 5th percentile female, 50th percentile male, and 95th percentile male anthropomorphic test devices (ATDs). All ATDs were outfitted with standard issue military combat boots and Advanced Combat Helmet (ACH) for every test. Additional tests were conducted with one of three additional military gear configurations (Figure 3) – Improved Outer Tactical Vest (IOTV) only, IOTV and Squad Automatic Weapon (SAW) Gunner set with a Tactical Assault Panel (TAP), and IOTV and Rifleman set with TAP. ATDs with the SAW Gunner and Rifleman gear sets were tested in the passenger configuration, while ATDs with helmet only and IOTV only were tested in the driver configuration. Two types of seatbelts, 3-point and 5-point seatbelts, with and without pretensioner(s) and load limiter(s), were also used. Pre-tensioners were used on the shoulder and lap belts, and were set to fire at 12ms. In tests using load limiters, a 4.9 kN load limiter was used on the shoulder of the 3-point belt, and 2x2.7 kN load limiters were used on the shoulders of the 5-point belt. Two tests used an Airbelt (inflatable shoulder belt and regular lap belt) in combination with a single pretensioner on the lap belt and one 4.9 shoulder belt load limiter. A complete matrix of the test series is shown in Table 1.

Figure 3: Military gear configurations

Each ATD was positioned based on UMTRI's seated solder posture recommendations (Reed and Ebert 2013), which was a volunteer study. The ATD posture was verified using a FaroArm digitizer. Head, neck, chest, and lower-extremity injury measurements from the ATDs, as well as the belt loads, were collected in each test. Multiple high-speed video cameras were also used in each test to record the kinematics of the ATDs.

Table 1: Sled test matrix.
PT: Pre-tensioner, LL: Load limiter

Test ID	Side	ATD Size	IOTV	Gear	Seat belt	
					Type	PT+LL
TD1403	Driver	50th	N	N	5-pt	N
TD1404	Driver	50th	Y	N	5-pt	N
TD1405	Driver	50th	N	N	3-pt	N
TD1406	Driver	50th	Y	N	3-pt	N
TD1407	Passenger	50th	Y	SAW Gunner	5-pt	N
TD1408	Passenger	50th	Y	SAW Gunner	3-pt	N
TD1409	Passenger	50th	Y	SAW Gunner	5-pt	Y
TD1410	Passenger	50th	Y	SAW Gunner	3-pt	Y
TD1411	Passenger	95th	Y	SAW Gunner	3-pt	Y
TD1412	Passenger	95th	Y	SAW Gunner	5-pt	Y
TD1413	Passenger	95th	Y	SAW Gunner	3-pt	N
TD1414	Passenger	95th	Y	SAW Gunner	5-pt	N
TD1415	Driver	5th	Y	N	5-pt	N
TD1416	Driver	5th	Y	N	3-pt	N
TD1417	Driver	50th	Y	N	3-pt	Y
TD1418	Driver	50th	Y	N	5-pt	Y
TD1419	Passenger	50th	Y	Rifleman	5-pt	Y
TD1420	Passenger	50th	Y	SAW Gunner	3-pt Airbelt	Y
TD1421	Passenger	50th	Y	Rifleman	3-pt	Y
TD1422	Driver	50th	Y	N	3-pt Airbelt	Y

The injury outcomes for each test were determined using each respective ATD's Injury Assessment Reference Values (IARVs) as shown in Table 2. The injury measures examined in the present study include the head injury criterion (HIC), neck tension (NeckT), neck compression (NeckC), neck injury criteria (Nij), chest acceleration (ChestG), chest deflection (ChestC), and left and right femur force (LFF, RFF).

The HIC is a measure of the likelihood of head injury resulting from an impact, and is defined as

$$HIC_{15} = max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5} (t_2 - t_1) \tag{1}$$

where a(t) is head acceleration as a function of time, and t_1 and t_2 represent a 15-ms time interval over the acceleration pulse.

The Nij measures the likelihood of neck injury using measured neck forces and moments normalized to critical injury tolerance levels determined from experimental testing. Nij is defined as

$$Nij = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}} \tag{2}$$

where F_z is the axial load on the neck, M_y is the flexion/extension bending moment of the neck, and F_{int} and M_{int} are the corresponding critical intercept values of load and moment, respectively, used for normalization. Nij is computed at all time instances, and the maximum value from all combination of loading modes (tension, compression, flexion, extension) is reported. In this manuscript, the results for each test are reported as a percentage of the ATD's respective IARVs.

Table 2: IARVs (Mertz et al. 2003).

Body Region	Injury Measure	95M ATD	50M ATD	5F ATD
Head	HIC-15	700	700	700
Neck	Nij Critical Intercept Values Ten and Comp (N) Flexion (Nm) Extension (Nm)	1.00 5440 415 166	1.00 4500 310 125	1.00 3370 155 62
	Neck axial tension (kN)	5.44	4.17	2.62
	Neck compression (kN)	5.44	4.0	2.52
Chest	Chest acceleration (g)	55	60	60
	Chest deflection (mm)	70	63	52
Leg	Femur axial force (kN)	12.7	10	6.805

Computational Models

A set of finite element (FE) models, including the test buck, three ATDs (HIII 5th, 50th, and 95th), military gear configurations (helmets, IOTVs at different sizes, and SAW Gunner), and different seatbelts were developed and integrated together. The test buck model was developed based on the design CAD data. The ATD models were the LSTC public models as shown in Figure 4. The geometries of the models for military gears were based on the seated solider study (Reed and Ebert 2013) with simplification and modification. The seatbelt models were developed based on the seatbelt component tests on the webbing, retractor, pre-tensioner, and load limiter.

A subset (16) of the crash tests (excluding conditions with the Rifleman and Airbelt) were used to validate the FE models. For each simulation, the ATD model was positioned and postured based on the FaroArm data measured in the tests. The time histories of the ATD head, chest, and pelvis accelerations, chest deflection, femur forces, seatbelt forces, as well as the head and hip excursions were used to tune the models, so that occupant kinematics and injury risks can be accurately simulated. The parameters that were calibrated in the simulations included the seatbelt slack, material properties similar to the vest and other military gears, seatbelt to vest/gear contact, seatbelt routing, etc.

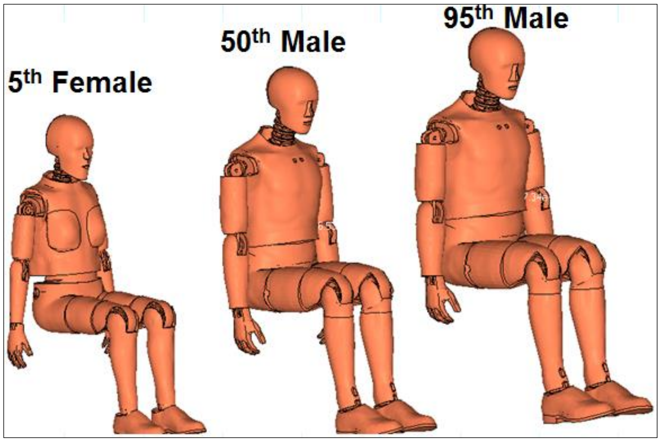


Figure 4: LSTC ATD models used in this study

RESULTS

General ATD kinematics in the sled tests

Figure 5 highlights two examples of ATD kinematics from the test series. Submarining-like behavior, which is defined as an excessive increase in hip excursion relative to the shoulder, occurred in 12 out of 20 tests. ATDs with IOTV only exhibited the most extreme submarining-like behavior. Although contact with the instrument panel or steering wheel occurred in 16 out of the 20 tests, in the majority of tests the contact occurred only to the helmet but not the head. There is generally a significant whipping motion to the ATD’s head, which is the main mechanism to generate the high HIC value and the Nij.

ATD Excursions in the sled tests

Since the sled test buck was not equipped with airbags or a knee bolster, forward excursions of the head, torso, and lower extremity were relatively large. Generally, head and knee excursions increased with ATD size (Figure 6). Since the 5th female ATD sat closest to the instrument panel, head contact was equally likely amongst all three ATD sizes. Military gear also influenced forward excursions, with excursions generally greater with ATDs outfitted with more military gears (such as the SAW Gunner and Rifleman) compared with ATDs outfitted with IOTV and helmet only (Figure 7). Pre-tensioners and load limiters tended to reduce forward excursions and limit head or helmet contact with the instrument panel or steering wheel (Figure 8). The 5-point belt showed an advantage over the 3-point belt in terms of belt fit and limiting excursions, while the ATDs using Airbelt system sustained significantly higher excursions than those using the 3-point and 5-point belt systems. Complete test results can be found in the Appendix.

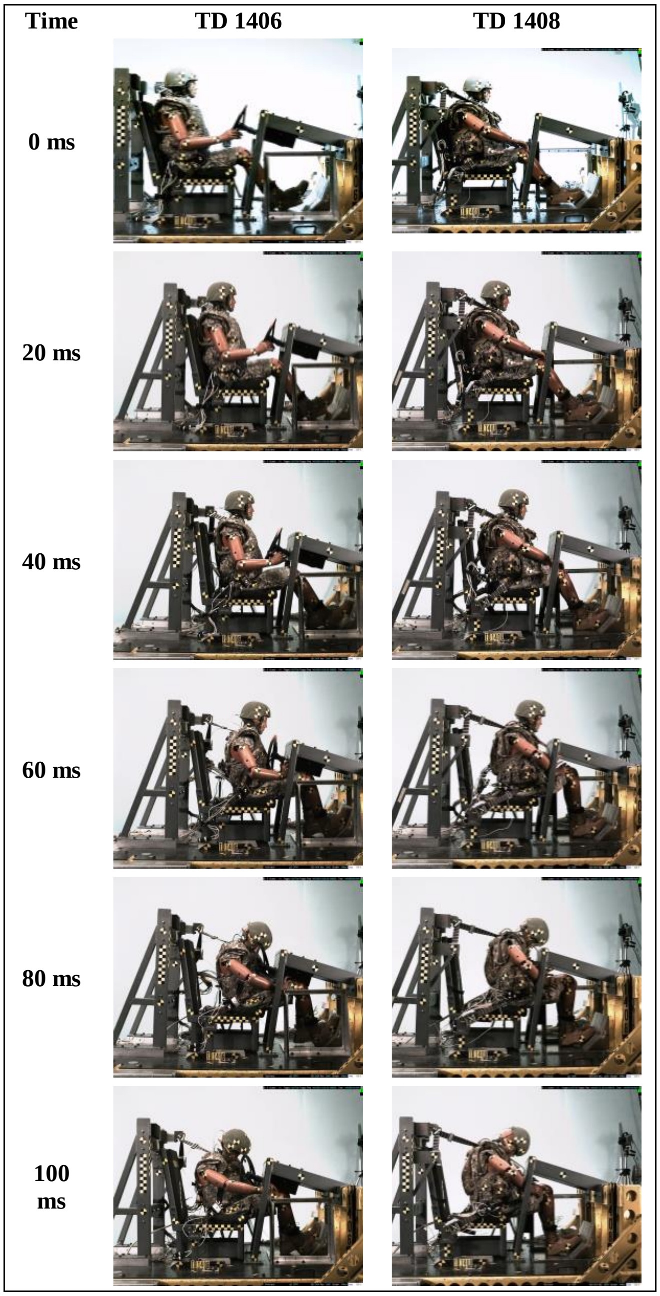


Figure 5: ATD kinematics for sled tests TD1406 (left column) and TD1408 (right column). Test TD1406 exhibited submarining-like behavior, with excessive forward excursion of the hip relative to the shoulder.

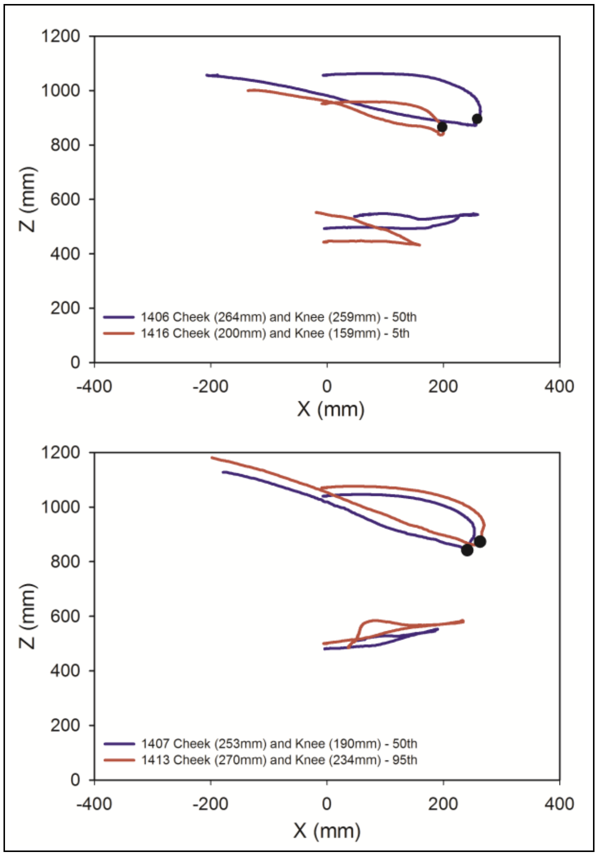


Figure 6: Representative forward cheek and knee excursions comparing the 50th and 5th ATDs (upper) and the 50th and 95th ATDs (lower). The black dot represents the point of contact with the steering wheel or the instrument panel.

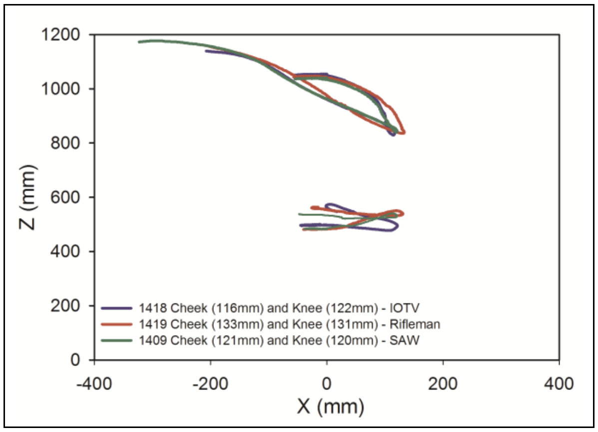


Figure 7: Representative traces showing the influence of military gears on forward cheek and knee excursions for the 5pt + PTLL belt tests.

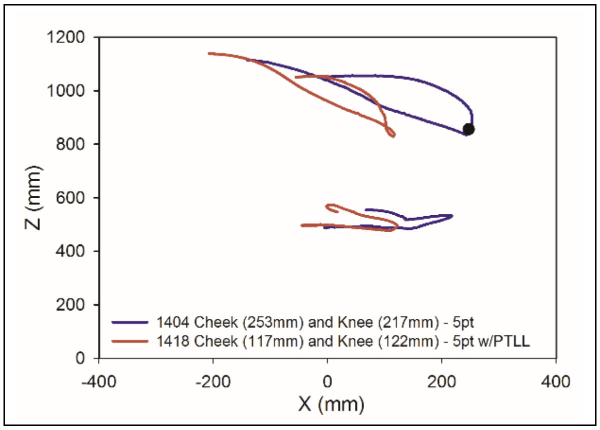


Figure 8: Example plot highlighting the influence of pre-tensioners and load-limiters on forward excursions.

Injury measures in the sled tests

As shown in Figure 9, femur compressive forces were well below injury thresholds in all tests, due to the lack of a knee bolster. HIC values were also all below the IARVs. Military gear had the most substantial influence on injury measures, with increased NeckT and Nij seen in ATDs outfitted with IOTV and other military gears compared with ATDs outfitted with the helmet (ACH) only (Figure 9). Military gear also tended to decrease chest accelerations, although the decrease was not statistically significant due to the low sample size.

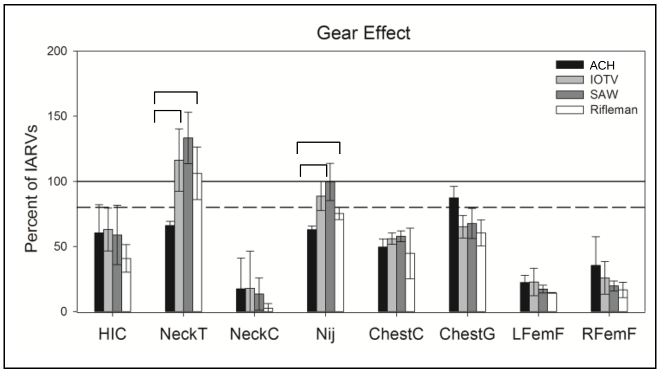


Figure 9: The influence of military gear on injury measures for the 50th ATD. The solid black line represents the level of the normalized 100% of the IARVs, and the dashed black line represents 80% of the IARVs. Data presented as means ± standard deviation. Brackets indicate statistically significant difference between two groups, as determined by a two-way ANOVA ($p < 0.05$).

Model development

Figure 10 shows an example of positioning the ATD, adding IOTV, helmet, and Saw Gunner onto the ATD body, and integrating the ATD, military gear, and seatbelt models into the sled buck model.

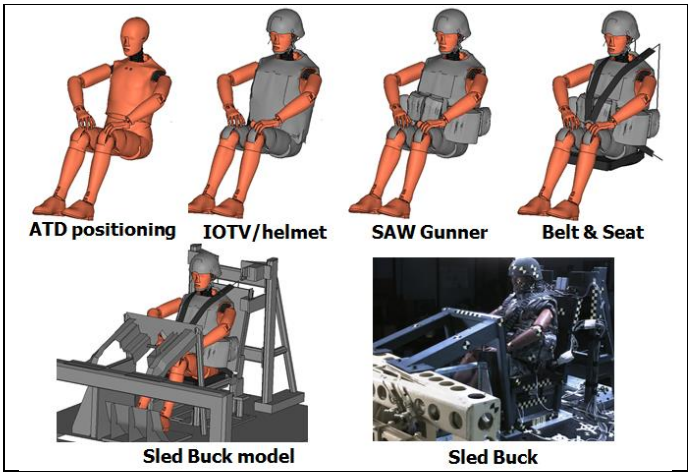


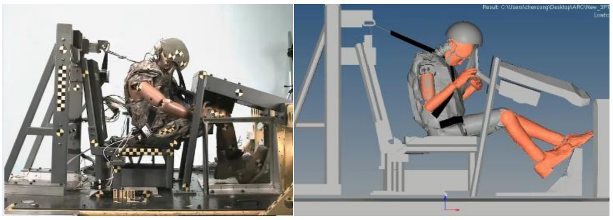
Figure 10: An example of building FE models to simulate the crash condition

Model validation

Generally speaking, good agreements between the tests and simulations were achieved. Examples of model kinematic validation are shown in Figure 11. Examples of model injury measure validation are shown in Figures 12 and 13.

a) 50th ATD / IOTV / 5pt belt

b) 50th ATD / SAW Gunner / 5pt belt with PT+LL



c) 5th ATD / IOTV / 3pt belt

Figure 11: Examples of model kinematic validation

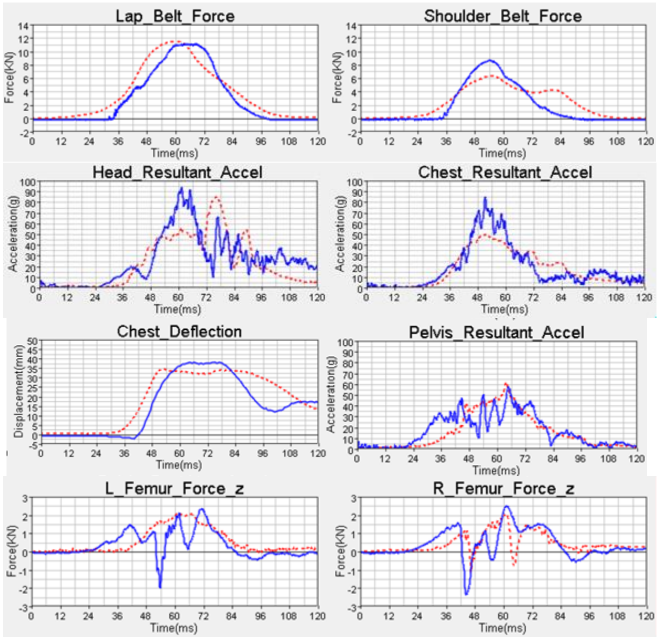


Figure 12: Model injury measure validation for 50th ATD with IOTV and 5pt belt (Red: test / Blue: simulation)

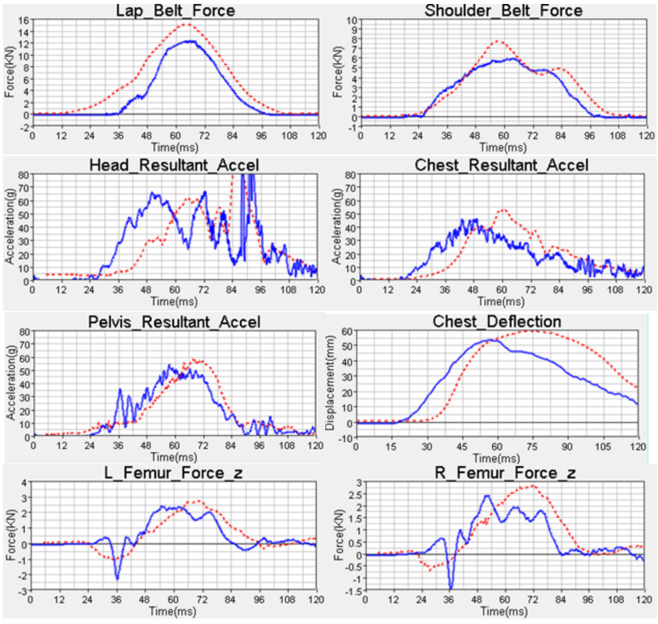


Figure 13: Model injury measure validation for 95th ATD with Saw Gunner and 5pt belt (Red: test / Blue: simulation)

DISCUSSION

This paper examined the influence of ATD size, military gear, and restraint system on the kinematics and injury measures of the Hybrid III ATDs in a representative light tactical vehicle environment under frontal crash conditions. To accomplish this goal, a combination of physical sled tests and computer simulations were conducted. The results demonstrate that kinematics and injury measures are highly influenced by occupant size, military gears, and restraint systems.

The sled tests demonstrated that ATDs in an environment similar to light tactical vehicles exhibit significantly different occupant kinematics than are typically seen in passenger vehicles. The lack of a knee bolster allowed for large lower extremity excursions and very low femur compressive forces. Since there was no airbag, head and chest excursions were also elevated, leading to a high chance of contact with the steering wheel or instrument panel. Most contacts, however, were with the helmet and not the ATD head. Therefore, the high neck injury measures seen in the tests were likely due to head whipping and not direct force applied to the head. This suggests that neck injury may be one of the major concerns in these testing conditions.

In the sled test series, military gear had the most significant influence on excursions and injury outcomes. Chest accelerations were decreased with gear, likely due to the IOTV adding the weight and distributing the seat belt load across the entire chest. However, the observed decreases in chest accelerations were accompanied by significantly elevated head and neck injury measures. These increases could be explained by the increased mass and changes in belt loading that occur when military gear is used. The chest deflection results were all below the injury threshold, which is likely due to the protection and restraint load distribution from the IOTV. Finally, our results also suggest that pre-tensioners and load limiters are effective in reducing forward excursions in ATDs outfitted with military gear. However, they did not reduce the injury measures significantly, especially the head and neck, because such injury measures were mainly caused by the head whipping motion. This result also suggests that adding airbag and optimizing the load limit may be necessary to further improve the protection of occupants in the current crash conditions.

During the model calibration process, we found that the seatbelt routing significantly affects the ATD kinematics and injury measures, especially for ATDs with the SAW Gunner configuration. It is understandable that the extra military gears may pose difficulty for wearing the seatbelt tightly, which will result in more initial slacks in the belt. The deformation of the gears may further reduce the tightness of the belt, which will lead to higher occupant excursions. The current validation results showed reasonable agreement to the test data, but can be further improved with optimizations.

This study provided valuable information about the effects from occupant size, military gear, seatbelt type, and advanced seatbelt features on occupant kinematics for a light tactical vehicle in frontal crashes. Future studies focusing computational optimization of the restraint system will be conducted.

ACKNOWLEDGEMENT

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REFERENCES

Forman, J., Lopez-Valdes, F., Lessley, D., Kindig, M., Kent, R., Ridella, S. and Bostrom, O., 2009. Rear seat occupant safety: an investigation of the progressive force-limiting, pretensioning 3-point belt system using adult PMHS in frontal sled tests. Stapp Car Crash J 53, 49-74.

Grujicic, M., Bell, W.C., Pandurangan, B. and Glomski, P.S., 2011. Fluid/Structure Interaction Computational Investigation of Blast-Wave Mitigation Efficacy of the Advanced Combat Helmet. Journal of Materials Engineering and Performance 20, 877-893.

Harris, R., Griffin, L., Hayda, R., Roundtree, M., Bryant, R. and Rossiter, N., 1999. The effects of antipersonnel blast mines of the lower extremity. IRCOBI, 457-467.

Hu, J., Fischer, K., Lange, P. and Adler, A., 2015. Effects of Crash Pulse, Impact Angle, Occupant Size, Front Seat Location, and Restraint System on Rear Seat Occupant Protection. SAE Technical Paper 2015-01-1453.

Mertz, H.J., Irwin, A.L. and Prasad, P., 2003. Biomechanical and scaling bases for frontal and side impact injury assessment reference values. Stapp Car Crash J 47, 155-188.

Newberry, W., Lai, W., Carhart, M., Richards, D., Brown, J. and Raasch, C., 2006. Modeling the effects of seat belt pretensioners on occupant kinematics during rollover. SAE Technical Paper 2006-01-0246.

Reed, M.P. and Ebert, S.M., 2013. The Seated Soldier Study: Posture and Body Shape in Vehicle Seats. UMTRI-2013-13.

APPENDIX – FULL SLED TEST RESULTS

	ATD	Position	Gear	Seat Belt	HIC-15	NeckT (N)	NeckC (N)	Nij	ChestC (mm)	ChestG (g)
TD1403	50th	Driver	ACU	5-point	530.4	2666.3	33.5	0.61	28.4	56.2
TD1404	50th	Driver	IOTV	5-point	448.7	5743.5	491.5	0.95	34.2	47.9
TD1405	50th	Driver	ACU	3-point	315.5	2852.4	1369.2	0.65	34	48.7
TD1406	50th	Driver	IOTV	3-point	366.6	3992.1	2739	0.79	32.6	37.6
TD1407	50th	Passenger	SAW	5-point	443.9	6325.6	421	1.07	35.6	48.4
TD1408	50th	Passenger	SAW	3-point	480.2	5061.3	1278.1	0.86	37	45.3
TD1409	50th	Passenger	SAW	5-pt w/PTLL	197.6	4968.4	152.2	1.06	37.4	30.3
TD1410	50th	Passenger	SAW	3-pt w/PTLL	322.7	4873	74.5	0.83	32.6	40.1
TD1411	95th	Passenger	SAW	3-pt w/PTLL	410.3	5865.5	26.5	0.85	36.6	44.9
TD1412	95th	Passenger	SAW	3-point	541.6	6746.1	1069.9	1.07	46.2	55.9
TD1413	95th	Passenger	SAW	5-point	475.7	7412.8	15.4	0.92	58.9	50.4
TD1414	95th	Passenger	SAW	5-pt w/PTLL	208.8	5027.6	145.9	0.66	47.1	32
TD1415	5th	Driver	IOTV	5-point	627.4	3594	80.2	0.97	29.8	52
TD1416	5th	Driver	IOTV	3-point	663.2	2863.2	245	0.93	27	49.8
TD1417	50th	Driver	IOTV	3-pt w/PTLL	626.8	3577.7	105.4	0.78	37.2	37.4
TD1418	50th	Driver	IOTV	5-pt w/PTLL	326.4	5664.6	234.9	0.87	39.2	34.1
TD1419	50th	Passenger	Rifleman	5-pt w/PTLL	233.4	5028.2	207.5	0.79	36.8	32
TD1420	50th	Passenger	SAW	3-pt airbelt	616.6	6586.9	776.5	1.16	39.7	39.1
TD1421	50th	Passenger	Rifleman	3-pt w/PTLL	338.3	3832.5	13.4	0.72	19.5	40.5
TD1422	50th	Driver	IOTV	3-pt airbelt	439.9	5281.4	3.3	1.04	33.3	38.4

	LFF (N)	RFF (N)	Lap Belt Load (N)	Shoulder Belt Load (N)	Lap Payout (mm)	Shoulder Payout (mm)	Peak forward excursions (mm)				
							Helmet	Cheek	Shoulder	Hip	Knee
TD1403	1847	1993	11789	5286	33	31	459	313	234	155	181
TD1404	2059	2035	12036	5976	18	21	371	233	214	202	217
TD1405	2628	5113	9305	10196	98	58	460	308	220	202	215
TD1406	4110	3281	8383	11110	121	33	419	264	216	246	259
TD1407	1628	2217	13475	6514	17	24	398	253	225	203	190
TD1408	2038	2336	9192	10026	130	30	464	304	317	302	295
TD1409	1277	1387	9951	4960	78	74	340	181	169	168	154
TD1410	1774	1801	7885	7916	101	93	447	288	278	203	185
TD1411	2117	2844	8183	7110	132	101	436	279	255	256	234
TD1412	2793	3875	10948	13390	135	21	452	297	372	363	336
TD1413	2802	2905	14442	7773	25	29	434	270	254	245	234
TD1414	2139	2129	11661	4960	89	89	371	214	193	192	192
TD1415	1455	2492	9441	5294	19	19	340	191	177	142	148
TD1416	1449	1932	5905	8950	75	30	314	200	182	148	158
TD1417	1866	1604	7690	7837	110	119	539	313	226	206	144
TD1418	1512	4484	9167	5076	45	50	321	166	142	158	161
TD1419	1419	1254	9769	5284	82	84	315	169	182	135	167
TD1420	1933	2120	6641	6892	135	197	551	407	392	235	210
TD1421	1461	2090	8282	7799	135	135	489	308	361	221	213
TD1422	1830	1571	7785	5079	104	197	549	390	309	157	164