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Critical Review of Anthropomorphic Test Device Anthropometry and Body Mass Distribution for Use in the Military Environment

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Anthropomorphic testing devices (ATDs) provide a repeatable way to evaluate military seating systems. Military design standards, such as those set forth in standards MIL-S-85510 and MIL-S-58095 (AV) for helicopter cabin seats, outline the pass/fail criteria for testing seat strength with various occupant sizes and weights (Department of Defense [DoD], 1981; DoD, 1986). Rhodes et al. (2021) determined that the total weight of the Soldier and their equipment had increased since these standards were released. Recommended injury assessment reference values (IARVs) specific to military scenarios have been made (Air Force Life Cycle Management Center [AFLCMC], 2016; Bartol et al., 1990; Rhodes et al., 2022a; Rhodes et al., 2022b). Commercially available ATDs are commonly developed from their predecessors and components are reused if IARVs are associated with them. Researchers from the U.S. Army Aeromedical Research Laboratory reviewed commercially available ATDs for their applicability to the military environment.

15. SUBJECT TERMS

body mass distribution, ATD, anthropometric test device, military IARVs, injury assessment reference values, extremities, impact, anthropometry

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Whole-body ATD anthropometry, shared components (i.e., head, neck, etc.), compatible extremities, validated impact directions, IARVs, and limitations were reviewed for each standard ATD. More recent U.S. Army Soldier anthropometry was reviewed and compared to each ATD according to the percentile size of the ATD. Extremities, such as upper or lower extremities and heads, were reviewed for their validated impact directions, IARVs, ATD compatibility, and limitations. A brief summary of each ATD is given with recommendations for use in the military environment along with limitations for their use.

Executive Summary

Anthropomorphic test devices (ATDs) provide a repeatable way to dynamically evaluate military seating systems. Military design standards, such as those set forth in standards MIL-S-85510 and MIL-S-58095 (AV) for helicopter cabin and pilot seats, respectively, outline the pass/fail criteria for testing seat performance with various occupant sizes and weights (Department of Defense [DoD], 1981; DoD, 1986). Rhodes et al. (2021) determined that the total weights of the Soldier and their equipment had increased since these standards were released. Accurate ATD body mass distribution allows the investigation of measured responses to impact and other mechanical forces (Tri-Service Aeromedical Research Panel [TSARP], 1988). The weight, size, and mass distribution of ATDs used by the military for testing and research should reflect the current Soldier population anthropometry to properly assess occupant safety for a given vehicle impact condition (Rhodes et al., 2021). In order to assess injury risk, the recommended injury assessment reference values (IARVs) specific to military scenarios should be used (Air Force Life Cycle Management Center [AFLCMC], 2016; Bartol et al., 1990; Rhodes et al., 2022a; Rhodes et al., 2022b). Researchers from the U.S. Army Aeromedical Research Laboratory reviewed past and present ATDs for their applicability to the military environment. Whole-body ATD anthropometry, common components (similar parts used in the construction of ATDs), compatible components (interchangeable parts that could be used on different ATDs), validated impact directions, IARVs, and limitations were reviewed for each standard ATD. The latest U.S. Army Soldier anthropometry dataset was reviewed and compared to each ATD according to the percentile size of the ATD. The alternate heads and extremities (upper/lower arms and legs) compatible with ATDs were reviewed for their validated impact directions, IARVs, ATD compatibility, and limitations. A brief summary of each ATD is given with recommendations for use in the military environment along with limitations of their use.

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Introduction

Anthropomorphic test devices (ATDs) are instrumented human surrogates used to assess human injury risks and/or the effectiveness of occupant protection systems during dynamic events. Various ATD designs are available to represent different occupant sizes and to meet biofidelity requirements for specific impact loading conditions. Instrumentation incorporated into the ATDs can vary depending on the body regions of interest and funding resources available to support the research or testing program. The most common ATD design available today in the U.S. is the Hybrid III (HIII), which is used extensively throughout the civilian automotive industry during vehicle development testing and to demonstrate compliance with the Federal Motor Vehicle Safety Standard (FMVSS) occupant protection requirements. Unfortunately, civilian automotive industry ATDs may not be well-suited for the conditions experienced in the military environment (Rhodes et al., 2022a; Rhodes et al., 2022b).

Military vehicle acceleration loading conditions can vary substantially from those commonly experienced in the civilian sector because of the operating conditions and vehicle response to external impacts (McEntire et al., 2025). These loading conditions can cause variations in the direction, magnitude, and duration of acceleration experienced by the occupants. For example, armored combat ground vehicles are designed primarily to protect occupants against kinetic threats, and the interiors are robustly designed to withstand the rigors of combat environments. While seat orientations in civilian automobiles are almost always forward facing, military seating orientations in both aviation and ground vehicle platforms vary to include forward, aftward, or sideward facing relative to the vehicle. Some crew positions, such as gun turrets with 360-degree rotation capabilities or door gunners, may require the occupant to take a standing posture. Additionally, military personnel are often encumbered with personal protective equipment (PPE), combat equipment, and survival gear that adds weight and bulk to the wearer. This wearer-borne equipment has potential to alter the loading paths to the occupant, influence occupant inertial response, and could also provide protective capabilities. Since civilian vehicle occupants do not wear PPE, ATDs designed for civilian automotive environments are not required to accommodate wearer-borne gear.

U.S. military materiel developers and researchers have used various ATD designs in the research, development, and acquisition of protective systems such as aircraft ejection seats, crashworthy seats, and occupant restraint systems. These protective systems are intended to improve occupant survivability and injury mitigation during dynamic events. Instrumented ATDs are used as human surrogates to provide realistic occupant weight to the system being evaluated and to record inertial and contact responses. Other ATD uses by the military include ground vehicle underbelly blast events, parachute opening shock, windblast exposure, bomb suit evaluations, and vehicle crash tests. Factors to consider during ATD selection should include the anthropometry of the user population to be represented, direction of the primary impact for each ATD, and the primary body regions of interest.

A critical aspect of an ATD design is its biofidelity. Biofidelity is a measure of their ability to respond in a humanlike fashion. The HIII was designed for frontal (longitudinal) acceleration exposures and its torso and extremities respond appropriately. The inertial and flail response kinematics, and any resulting flail contact loads of the ATD torso and extremities are influenced by the ATD component dimensions, mass distribution, and segment joint designs. Deviations of these parameters from the intended human population for which the ATD was designed to represent can alter ATD sensor measurements during dynamic tests leading to incorrect injury risk assessments. Accurate ATD body mass distribution allows the investigation of measured responses to impact other mechanical forces (Tri-Service Aeromedical Research Panel [TSARP], 1988). To properly assess occupant safety for a given vehicle impact condition, the weight, size, and mass distribution of ATDs used by the military for protective equipment research, testing, development, and acquisition should reflect the anthropometry of the desired Service Member population (Rhodes et al., 2021). For this report, USAARL compiled a list of whole-body ATDs and ATD subsystems (e.g., extremities, head) potentially suitable for use in the dynamic loading conditions of different military environments, specifically air and ground vehicle impacts.

Backgrounds

Modern rotary-wing aircraft are designed with stringent occupant protection systems and aircraft crashworthiness requirements to improve occupant survivability and injury mitigation when mishaps occur (Coltman et al., 1989; Bolukbasi et al., 2011; Department of Defense [DoD], 1998). Consequently, the process of evaluating seating and restraint systems in U.S. Army rotary-wing aircraft differs from the process used in civilian vehicle testing because of the unique loading magnitudes and directions (i.e., vertical versus horizontal impacts). Military design standards, such as those set forth in standards MIL-S-85510 and MIL-S-58095A (AV) for helicopter occupant seats, outline the dynamic and static test conditions and performance criteria for various occupant sizes (DoD, 1981; DoD, 1986). However, Rhodes et al. reported that the total weight of the U.S. Army Soldier and equipment had increased since these standards were released; therefore, the weights used for testing may need to be updated in these standards (2021).

Head and extremity flail envelopes were developed for different restraint systems to assist military vehicle designers in identifying and mitigating occupant flail strike hazards during rotary-wing crash events. The Aircraft Crash Survival Design Guide (ACSDG) defines flail envelopes for the head, neck, torso, and extremities for the 95th percentile male (95M) with the use of a five-point conventional restraint system that meets MIL-S-58095A (AV) requirements (Desjardins, 1989; DoD, 1986). Anthropometric measures, such as sitting height, will influence the head flail trajectory during a dynamic event. Body mass distribution also affects the extent that occupant body segments will flail and affect the flail envelope accuracy.

Injury assessment reference values (IARVs), which are injury risk interpretations made from data collected using ATD embedded sensors, have been developed for different body regions of interest of specific ATD types and sizes. The IARVs were developed through matched-pair testing that compared data collected from post-mortem human subjects, human volunteers, and animal injury responses to the ATD responses under the same testing conditions. Injury correlations made from the matched-pair testing are specific to loading conditions, the body region tested, and the ATD type and size used. In order to interpret ATD measured response to possible human injury risk during dynamic military events, IARVs validated for a specific ATD design and developed from similar dynamic exposures must be selected (Rhodes et al., 2022a; Rhodes et al., 2022b). Some IARVs specific to military scenarios with corresponding impact directions have been recommended to assess injury risk (Air Force Life Cycle Management Center [AFLCMC], 2016; Bartol et al., 1990; Rhodes et al., 2022a; Rhodes et al., 2022b). It is important to note that if IARVs are not recommended for their intended purpose, then the ATD response metrics should only be used for comparative assessments.

Commercially available ATDs are commonly designed from their predecessors and often include common components. IARVs that were developed for those common components are frequently applied by researchers to assess injury. These ATD components may not have been developed and validated with conditions representative of the military environment; therefore, the components may not be appropriate for use in assessing injury for all loading conditions. Knowledge of the components that are common between different ATD types and validated dynamic exposure(s) are beneficial for understanding and properly applying IARVs to assess injury in military seating systems.

Methods

The U.S. Army Aeromedical Research Laboratory (USAARL) reviewed ATDs from the past 50 years, the most recently published Soldier anthropometry, and IARV data for assessing injury and injury risk. Literature describing ATDs was reviewed for applicability to the military environment. Figures and instrumentation tables for all reviewed ATDs are reported in Appendix A. Whole-body ATD anthropometry, common components (e.g., head, neck, extremities, etc.), compatible extremities, validated impact directions, IARVs, and limitations were reviewed. Updated U.S. Army Soldier body weight (BW) and sitting height, measured with the occupant hip, knee, and ankle angle each at a 90° (90-90-90) seated position was reviewed and compared to each ATD by anthropometric percentiles presented in Gordon et al. (2014). Male and female body mass distributions of body segments were then reviewed to determine their percentage of total BW (TSARP, 1988; R. Fellin, personal communication, December 15, 2022) and compared to ATD body segment mass distributions. Extremities (upper and lower) and heads were reviewed to understand their validated impact directions, IARVs, ATD compatibility, and limitations. Summary tables indicating how BW, sitting height, and body mass distribution compared to recommended values, if the ATD had a full or segmented arm, and if IARVs with corresponding impact direction were recommended for the military environment were created. A general schematic of potential ground/air vehicle seating orientations and vehicle impact directions was created to examine the impact direction for each seated occupant. Lastly, ATD recommendations were made based on impact direction, seating orientation, assessment type, and loading type. Available ATD sizes and number of sensor channels were also included to provide the reader with complete information.

Results

Twenty-three standard ATDs and six alternate extremities were reviewed for their historical development, anthropometry, common components, and compatible extremities. Primary impact direction for whole-body ATDs (anterior-posterior [AP], lateral, posterior-anterior [PA], and vertical) and available sizes for each are indicated in Table 1. Most ATDs reviewed represented the medium sized male for all primary impact directions. The HIII, Advanced Dynamic Anthropomorphic Manikin (ADAM), and the Large Anthropomorphic Research Dummy (LARD) were the only ATDs found that represent the large male. The ATDs available in a small female size were the Hybrid III (HIII), Test Device for Human Occupant Restraint (THOR), SID-II small (SID-IIs), World Side Impact Dummy (WorldSID), and the Lightest Occupant In Service (LOIS). It was noted that the only ATD that represents the small male was the Air Force ADAM ATD for the vertical primary use direction. We also noted that the Biofidelic Rear Impact Dummy II (BIORID-II) was the only ATD developed for the PA impact direction. Two arms, three legforms, and one headform were reviewed (Table 2). Compatible ATDs and primary impact direction for each extremity and headform was noted. Illustrations and typical sensor instrumentation of each ATD reviewed can be found in Appendix A.

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Table 1. Standard Whole-Body ATDs Reviewed for Application to Military Scenarios

Primary Impact Direction Use	Whole-Body ATD Identification	Available Sizes			
		Small Female	Small Male	Medium Male	Large Male
AP	Hybrid II (HII)			X	
	Hybrid III (HIII)	X		X	X
	Test Device for Human Occupant Restraint (THOR)	X		X	
Lateral	Side Impact Dummy (SID)			X	
	SID-HIII			X	
	SID-II small (SID-IIs)	X			
	European SID 2 (ES-2)			X	
	ES-2re (with rib extension)			X	
	World Side Impact Dummy (WorldSID)	X		X	
	Biofidelic SID (BIOSID)			X	
	Military SID (MIL-SID)			X	
PA	Biofidelic Rear Impact Dummy II (BIORID-II)			X	
Vertical	Advanced Dynamic Anthropomorphic Manikin (ADAM)		X		X
	Lightest Occupant In Service (LOIS)	X			
	Large Anthropomorphic Research Dummy (LARD)				X
	Warrior Injury Assessment Manikin (WIAMan)			X	
Vertical and AP	Federal Aviation Administration HIII (FAA-HIII)			X	
NA	PRIMUS			X	

Table 2. Commercially Available Alternate ATD Accessories Reviewed for Application to Military Scenarios

Primary Impact Direction Use	Alternate Accessory
AP, Lateral	HIII Instrumented Arm for 50th Percentile Male
Any exposure that may induce upper extremity flail	Society of Automotive Engineers (SAE) International® 5th Percentile Arm
AP	HIII Lower Extremity Legform (HIII-LX)
AP	THOR Lower Extremity (THOR-LX) Advanced Legform
Vertical	Military Lower Extremity (MIL-LX) Legform
AP, Lateral	Facial and Ocular CountermeasUres Safety (FOCUS) Headform

Description of Whole-Body ATDs Reviewed

Hybrid II (HII) Medium (50th Percentile Male [50M]).

The HII-50M was developed by the General Motors Corporation (GM) and later mandated in 1973 by the National Highway Safety Administration (NHTSA) to test automotive restraint systems for the AP direction. Use of this whole-body ATD was limited due to not being fully instrumented, and it lacked biofidelity in the head, neck, thorax, and knees (Landolt, 1996; Mertz & Irwin, 2015). The anatomical features of the HII-50M headform make it desirable for military applications involving headgear, such as helmets, oxygen masks, and helmet-mounted visual displays. The HII headform anthropometry features include eyes, nose, chin, nape, and upper neck flesh. These features are advantageous to repeatable placement and fitting of military headgear systems involving chin straps, nape straps, oxygen masks, and helmet-mounted visual displays. An illustration and typical sensor instrumentation for the HII can be found in Appendix Figure A1 and Table A1.

HIII Small Female (5th Percentile Female [5F]), 50M, and Large Male (95M).

The HIII-50M was created by GM in 1976 to evaluate restraint systems in the AP direction and address the limitations associated with the HII-50M ATD. The HIII was designed to have a higher level of biofidelity in the head, neck, thorax, and knees than the HII-50M. The HIII-50M was later scaled to represent the 5F and 95M (Mertz et al., 2001). The HIII ATD design is durable and provides reproducible test results (Mertz & Irwin, 2015); however, military headgear use on the HIII headform is problematic. These problems are associated with the anthropometry of the HIII headform which includes poor chin and nape definition, lack of upper neck flesh, and its blended facial features. These HIII headform issues influence the fit, placement, stability, and retention of military head-borne systems that can alter the ATD head response and performance in dynamic events. In addition, the absence of anatomical features and landmarks make it difficult to position the helmet on the head in a repeatable manner. The HIII ATDs are typically instrumented with linear accelerometers, load cells, and displacement transducers (Humanetics Innovative Solutions, Inc., 2017).

The HIII ATDs were designed for impact loading in the AP direction that is typically representative of automotive frontal impact events. Extensive testing with the HIII head and neck was conducted to develop IARVs for those regions (Rhodes et al., 2022a). The HIII comes standard with pelvis "flesh" molded for a sitting position but can also be acquired or retrofitted with a pedestrian pelvis that allows the femur to articulate to a standing posture. The pedestrian pelvis was developed to test interactions between a standing/walking pedestrian and a vehicle. Because of the increased hip range of motion of the pedestrian pelvis, researchers have employed the pedestrian pelvis in seated tests because it better accommodates variable seat pan and back angles; however, more evaluation of the seated pedestrian biofidelity is needed (Moffatt et al., 2003; Zhang et al., 2013). Illustrations and typical sensor instrumentation for the HIII-5F, 50M, and 95M ATDs can be found in Appendix Figure A2 and Table A2.

Test Device for Human Occupant Restraint (THOR) 5F and 50M.

The THOR-50M is an advancement of the HIII for impact loading in the AP direction. The abdomen, thorax, and pelvis of the HIII were modified to form the Trauma Assessment Device (TAD-50) created at the University of Michigan Transportation Research Institute (UMTRI) in the early 1990s under contract with the NHTSA (Mertz & Irwin, 2015) and the biodynamics development company, GESAC, Inc. (GESAC, Inc., n.d.). The neck and lower extremity (LX) were modified simultaneously by NHTSA Vehicle Research and Test Center. Both projects were combined to form an advanced, midsized adult male ATD called THOR (Mertz & Irwin, 2015). Improvements were made to the occipital condyles of the neck, the restraint interaction of the thorax and shoulder, and the biofidelic axial load response of the femur (Humanetics Group, 2023a). Additionally, the spine was designed with flexible thoracic and lumbar joints. Notably, the head was instrumented with a nine-accelerometer array (making angular acceleration calculations possible). Anterior and posterior cables were added to the cervical spine to mimic the anterior and posterior longitudinal ligaments. Finally, multiple tilt sensors were integrated into the THOR to aid in ATD pre-test positioning. An illustration and typical sensor instrumentation for the THOR-50M can be found in Appendix Figure A3 and Table A3. The THOR-5F was created recently to represent the smaller female population (Humanetics Group, 2023b). An illustration and typical sensor instrumentation for the THOR-5F can be found in Appendix Figure A4 and Table A4.

Side Impact Dummy (SID).

The first SID was developed in 1979 with UMTRI under contract with NHTSA for lateral impacts. The SID has no arm or shoulder structure, per se, and its chest structure has a hydraulic shock absorber between five steel ribs and the spine. The SID lacks instrumentation in the neck, shoulder, and abdomen (Mertz & Irwin, 2015). An illustration of the SID can be found in Landholt (1996). A detailed instrumentation list could not be found.

SID-HIII.

The SID-HIII is configured with the SID body and the HIII head and neck. It was developed to improve the SID biofidelity. In 1998, NHSTA specified the SID-HIII to evaluate side impact head airbags. While the HIII neck was designed for AP impacts, it has documented biofidelity in the lateral direction (Mertz & Irwin, 2015). Along with the HIII head and neck instrumentation, the SID-HIII has a modified HII thorax for side impact with accelerometers on the upper and lower ribs and the first and twelfth thoracic vertebrae. Notably, there is no shoulder joint; the arms are simulated with padding (van Ratingen & Bermond, 2003). An illustration and typical sensor instrumentation for the SID-HIII can be found in Appendix Figure A5 and Table A5.

SID-IIs.

For lateral impacts, the SID-IIs is the second generation of the SID and has anthropometry representative of a small adult female (Humanetics Innovative Solutions, Inc., 2015a). In 1994, the SID-IIs was developed because of the need for a small female test device to evaluate lateral impact protection countermeasures (Mertz & Irwin, 2015). The head, neck, and legs were based off the HIII-5F ATD and its instrumentation. The SID-IIs only includes one truncated arm which is installed on the side of impact; however, there is a multi-channel arm option with load cells, accelerometers, and rotation sensors (Humanetics Innovative Solutions, Inc., 2015a). Lastly, there is a single-use frangible, lateral pelvis insert. An illustration and typical sensor instrumentation for the SID-IIs can be found in Appendix Figure A6 and Table A6.

EUROSID-2 (ES-2) and ES-2 Rib Extensions (ES-2re).

The development of the ES-2 was coordinated by the European Experimental Vehicle Committee (EEVC) Working Group 12 in 2001 to address deficiencies with the EUROSID-1 (ES-1) (Mertz & Irwin, 2015). The ES-2 is a lateral impact ATD based on the ES-1 with improvements to the head, neck, shoulder, thorax, abdomen, pelvis, and legs. The NHTSA further modified the ES-2 by adding rib extensions to prevent the seatback foam from getting lodged into a gap that exists in the ES-2. This rib extension modification is designated as the ES-2re ATD (Mertz & Irwin, 2015). The instrumentation is the same in both the ES-2 and ES-2re, which includes the head equipped with a three axis accelerometer, linear potentiometers to measure rib deflection, and upper/lower neck load cells to measure lateral flexion (Humanetics Innovative Solutions, Inc., 2016a). An illustration and typical sensor instrumentation for the ES-2/2re can be found in Appendix Figure A7 and Table A7.

WorldSID-5F and 50M.

The WorldSID-50M ATD was developed in 2001 in an attempt to harmonize all lateral impact SIDs and replace the SID-II, SID-HIII, ES-2, ES-2re, and BIOSID. They are available with reversible arms for left or right impact, full or half arms, a flexible lumbar spine, an instrumented pelvis and upper/lower legs (Humanetics Group, 2023d). An illustration and typical sensor instrumentation for the WorldSID-50M can be found in Appendix Figure A8 and Table A8. In 2004, development of the WorldSID-5F began with the approach to scale down the WorldSID-50M (Humanetics Group, 2023c; Mertz & Irwin, 2015). The WorldSID-5F includes an infra-red telescoping rod for the assessment of chest compression (IR-TRACC) for measuring rib displacement. An illustration and typical sensor instrumentation for the WorldSID-5F can be found in Appendix Figure A9 and Table A9.

Biofidelic SID (BIOSID).

SAE International developed the BIOSID for lateral impact testing in 1989 after recognizing the limited biofidelity of the SID-II, ES-2, and ES-2re ATDs (Franklyn & Lee, 2017). The BIOSID has a modified ES-2 pelvis, with a crushable block in the pivot center of the torso and thigh (Landolt, 1996). An IR-TRACC system measures compression in the shoulders and ribs. Full and truncated arms are available. The BIOSID also has the same head, neck, and legs as the HIII, and has been found to be durable, well documented, and reproducible (Landolt, 1996). Other instrumentation includes two tilt sensors to assist with positioning, six-axis load cells that can be moved to different locations in the femur or tibia depending on data needed, and potentiometers in the ankles. An illustration of the BIOSID can be found in Landholt (1996). A detailed instrumentation list could not be found.

Military SID (MIL-SID).

Military vehicle blast testing revealed that vehicle occupants can experience large lateral forces. Thus, the MIL-SID was developed for the military environment to evaluate mine blasts to vehicles and is capable of measuring lateral and vertical forces. This ATD was developed from the ES-2re torso and upper legs combined with the head and neck of the HIII-50M and a new lower neck load cell (Humanetics Group, 2023e). An illustration and typical sensor instrumentation for the MIL-SID can be found in Appendix Figure A10 and Table A10.

Biofidelic Rear Impact Dummy II (BIORID-II).

The BIORID-II ATD was designed in the late 1990s to assess neck injury during rear impacts, specifically whiplash (Mertz & Irwin, 2015). This ATD has 24 fully articulated vertebra (seven cervical, twelve thoracic, and five lumbar vertebrae) made of durable plastic connected with pins. Tensioning cables have been incorporated into the neck design to increase neck biofidelity. Validation testing was conducted with volunteers in low impact exposures. Accelerometers are located at the head, first and eighth thoracic vertebrae, first lumbar vertebra, and pelvis. Other instrumentation includes angular rate sensors, load cells, and tilt sensors throughout the spine (United Nations Economic and Social Council, 2022). An illustration and typical sensor instrumentation for the MIL-SID can be found in Appendix Figure A11 and Table A11.

Advanced Dynamic Anthropomorphic Manikin (ADAM).

The ADAM ATD was developed by System Research Laboratories (SRL) under contract to the U.S. Air Force for the assessment of ejection seat performance (vertical impact) and other applications, such as testing of parachutes and helicopter seat crashworthiness (Landolt, 1996). The ADAM was designed with adjustable friction mechanisms in each joint to capture passive muscle forces, range of motion of joints that replicate human articulation, and approximate human body segment contours, weights, moments of inertia, centers of gravities, and joint centers of rotation. The spinal system was designed to mimic human spine compression in the *z*-axis yielding a realistic response that varies with the force applied. However, the thoracic spine design does not permit flexion, extension, or lateral bending. The ADAM ATD is available in two male sizes, large and small (Landolt, 1996). A female version of ADAM was not developed. An illustration of the ADAM and its instrumentation can be found in Appendix Figure A12 and Figure A13. A detailed instrumentation list could not be found.

LOIS and LARD.

In 1994, the Joint Primary Aircraft Training Systems (JPATS) was tasked to design a joint service (U.S. Air Force and U.S. Navy) aircraft for primary aviator training. The aircraft is equipped with ejection seats and needed to accommodate an extreme anthropometric range for male and female aviator trainees. This resulted in the need for JPATS to define a set of anthropometric conditions (i.e., short and lightweight, short and heavy, tall and lightweight, and tall and heavy) for each sex for designing the aircraft cockpit and ejection seat. Two ATD designs emerged from this effort for use in the JPATS ejection seat testing, the small female called the LOIS, and the LARD.

The LOIS was developed from the 5th percentile Very Important Person (VIP) ATD (no longer used) and accommodated two head sizes, the Joint Strike Fighter (JSF)-SF74A and the JSF-SF81H (Bartol et al., 1990) for ejection seat testing (vertical impact). The shoulder design of LOIS is the same as the HIII-5F ATD, with the exception that the LOIS shoulder is made of aluminum and the clavicle links are modified for a universal chest box. The arms and legs of LOIS are slightly modified from the HIII-5F ATD to meet length and BW requirements. An illustration and typical sensor instrumentation for the LOIS can be found in Appendix Figure A14.

The LARD ATD was developed to represent the largest occupant in service for ejection seat testing (i.e., vertical impact). Two heads were designed for this ATD, an ADAM-type head molded from the HII ATD with ears and the JSF-LM110 head developed from a scanned human head. The LARD ATD shares the HIII-95M neck, shoulder (with bronze clavicle link), and the HIII-95M pedestrian pelvis. The arms and legs were also lengthened to meet U.S. Air Force requirements. An illustration and typical sensor instrumentation for the LARD can be found in Appendix Figure A15.

Warrior Injury Assessment Manikin (WIAMan).

The WIAMan is a relatively new ATD. It was developed by the U.S. Army around 2012 in conjunction with academic and industry partners for use in under belly blast (UBB) testing of military ground vehicles and vehicle components (Reed, 2013). The anthropometry, sitting height, and body mass distribution are representative of the 50M Soldier. However, data for body mass distribution could not be found during this literature review to verify the data. The ATD is designed to capture the response to military loading modes and seating positions more accurately than the HIII ATD family (Pietsch et al., 2016). The WIAMan was engineered to support collecting over 150 channels of sensor data with an internally integrated SLICE6 (Diversified Technical Systems [DTS], Seal Beach, CA) modular data acquisition system (DTS, 2022). An illustration and typical sensor instrumentation for the WIAMan can be found in Appendix Figure A16 and Table A12.

Federal Aviation Administration Hybrid III (FAA-HIII) 50M.

In 1999, development of the FAA variant of the HIII started with modifications to the HIII-50M for an ATD to be used in assessing crashworthy aircraft seat performance under vertical accelerations. Previously, the FAA specified the HII ATD for aircraft and aircraft seat testing. The modifications included replacing the HIII curved lumbar spine with a straight spine, and substituted weighted femurs to maintain the correct body weight for aircraft seat certification tests. Other notable differences are the inclusion of the HII chest flesh, lower torso, and upper legs to allow torso bending over the lap belt and lumbar compressive force measurement (Humanetics Innovative Solutions, Inc., 2021). An illustration and typical sensor instrumentation for the FAA-HIII can be found in Appendix Figure A17 and Table A13.

PRIMUS.

Crashtest-Service (CTS) (Munster, Germany) has introduced a new ATD design named PRIMUS, which is still under testing. There are two PRIMUS versions available. One version is constructed with a frangible skeleton, soft tissue, and tendon surrogates with biofidelic material properties. The intent of this design is for the frangible PRIMUS ATD to sustain damage in car crash tests that would be representative of injuries likely to be sustained by human occupants in the same event. No instrumentation is included in this PRIMUS version as the outcome is reported by documenting the physical damage it sustained during the test. During reconstructions of real-world accidents, testers have reported damage patterns observed in PRIMUS frangible components to be similar and representative of the actual injuries sustained (CTS, 2023). The second PRIMUS version is more similar to current ATDs and is constructed with stronger skeleton components with instrumentation to measure forces, moments, and accelerations, etc. An illustration of the PRIMUS can be found in Appendix Figure A18. A detailed instrumentation list could not be found.

Description of Extremities Reviewed

HIII-50M Instrumented Arm.

Instrumented upper extremities (arms) are available for the HIII-50M and are purchased separately. The upper extremity kit was developed based on the work of Saul et al. (1996). Limited information on availability and instrumentation was found.

SAE HIII-5F Instrumented Arm.

The SAE International, Inc. HIII-5F instrumented arm was previously used by the U.S. Army to assess arm injury risk due to airbag deployment in the Cockpit Airbag System (CABS) program (Duma et al., 2004). The multi-channel arm option has load cells, accelerometers, and elbow rotation sensors (Humanetics Group, 2023f).

THOR-LX Advanced Legform.

Designed for vehicular frontal impact testing, the THOR-LX exhibits improved biofidelic response and is compatible with the THOR-50M and the HIII 50th percentile ATDs. The ATD design includes an Achilles tendon representation, human-like foot performance in dynamic loading, and compliant axial loading in the tibia shaft. Instrumentation includes foot/leg linear accelerometers, upper tibia, lower tibia, Achilles load cells, and rotary sensors in the ankle (Humanetics Group, 2023g).

MIL-LX.

The MIL-LX legform was developed by incorporating key aspects of the standard HIII-50M lower leg and THOR-LX leg to analyze anti-vehicular land mine countermeasure effectiveness (Humanetics Group, 2023h). The leg is designed to measure vertical forces and accelerations to simulate PMHS response to blast-induced axial loading. An HIII-50M style foot was used and includes an energy-absorbing pad in the heel. The ankles of the MIL-LX legform and the THOR-LX have similar centers of rotation. Instrumentation includes linear accelerometers on the foot/leg, upper tibia, and lower tibia load cells (Humanetics Group, 2023h).

FOCUS.

The FOCUS headform was developed by the U.S. Army to address the potential for face and ocular injuries to aviators due to the interaction between airbags and equipment (e.g., night vision goggles, helmet mounted displays) (Weisenbach et al., 2020). The face of the FOCUS was instrumented with load cells to measure the forces acting on the frontal and nasal bones in the AP and lateral directions, maxilla in the AP direction, and zygoma in the lateral direction. Instrumentation includes five tri-axial load cells for the facial bones and two uni-axial load cells for the eyes. Matched-pair impact testing with the FOCUS headform and male PMHS was performed using a gravity-driven drop tower to develop injury risk values. The risk of bone fracture in the PMHS was determined and the biofidelity of FOCUS was evaluated. The FOCUS headform was designed to be compatible with the HIII-50M neck as an alternative to the HIII headform. The head anthropometry of FOCUS was based on a USAARL midsize headform previously designed to satisfy the midsize male aviator head anthropometry reported by TSARP.

Soldier Anthropometry

The most recently measured Soldier population anthropometry was reported in the second Anthropometric SURvey of U.S. Army personnel (ANSUR II) by Gordon et al. (2014). The BWs and sitting heights for the 5F, 50M, and 95M Soldiers were referenced and compared to the respective-sized ATDs. The closest percentile that the ATD BW and height represented in the Soldier population was reported (Tables 3, 4, and 5). The BW of the HIII-5F, HIII-50M, HIII 95, THOR-5F, THOR-50M, PRIMUS, SID-HIII, WorldSID-5F, LOIS, LARD, and WIAMan were within 10% of the reported values in ANSUR II. The BW of the HII-50M, FAA-HIII, SID IIs, ES-2/2re, WorldSID-50M, and the large ADAM were between 10%–15% of the reported values in ANSUR II. The small ADAM was the only ATD that deviated over 20% of the reported values in ANSUR II. Finally, all ATD sitting heights fell within 10% of the recommended values reported in ANSUR II.

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Table 3. BW and Sitting Heights of the ANSUR II 5F Soldier and 5F Representative ATDs (AFLCMC, 2016; Gordon et al., 2014; Humanetics Innovative Solutions, Inc., 2015a, 2020; Humanetics Group, 2023a, 2023c)

	Total BW				**Sitting Height**			
Small Female	**Reported BW (lb)**	**Difference from ANSUR II (lb)**	**Approximate ANSUR II BW Percentile***	**Percent Change (PC) in BW**	**Reported Sitting Height (in.)**	**Difference from ANSUR II (in.)**	**Approximate ANSUR II Sitting Height Percentile***	**PC in Sitting Height**
ANSUR II 5F	113.1		5th		31.6		5th	
HIII-5F	108	-5.1	<3rd	-4.5	31	-0.61	2nd	-1.9
THOR-5F	104.3	-8.8	<2nd	-7.8	31	-0.61	2nd	-1.9
SID-IIs	96**	-17.1	<1st	-15.1	30.7	-0.91	1st	-2.9
WorldSID-5F	108.5***	-4.6	<3rd	-4.1	30	-1.61	<1st	-5.1
LOIS	103	-10.1	1st	-8.9	32.7	+1.09	22nd	+3.4

Note. Dark gray denotes no calculation.

*Value rounded to the nearest percentile.

**Weight indicated is with one truncated arm and no chest jacket.

***WorldSID-5F ATD BW with full arms and dummy suit.

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Table 4. BW and Sitting Heights of the ANSUR II 50M Soldier and 50M Representative ATDs (AFLCMC, 2016; Bartol et al., 1990; Exponent Failure Analysis Associates, 2004; Gordon et al., 2014; Humanetics Group, 2023i; Humanetics Innovative Solutions, Inc., 2017, 2021; Humanetics Group, 2023b; Humanetics Innovative Solutions, Inc., 2016a, 2016b, 2018; Kistler Group, 2022; Reed, 2013; van Ratingen & Bermond, 2003)

	Total BW				**Sitting Height**			
Medium Male	**Reported BW (lb)**	**Difference from ANSUR II BW (lb)**	**Approximate ANSUR II BW Percentile***	**PC in BW**	**Reported Sitting Height (in.)**	**Difference from ANSUR II Sitting Height (in.)**	**Approximate ANSUR II Sitting Height Percentile***	**PC in Sitting Height**
ANSUR II 50M	186.5		50th		36.1		50th	
ADAM (Small Male)	142.3	-44.2	5th	-23.7	34.5	-1.6	11th	-4.5
HII	164	-22.5	22nd	-12.1	35.7	-0.4	40th	-1.2
HIII-50M	171.3	-15.2	30th	-8.2	34.8	-1.3	15th	-3.7
FAA-HIII	166.2	-20.3	25th	-10.9	35.8	-0.3	40th	-0.9
THOR-50M	168.9	-17.6	28th	-9.4	35.7	-0.4	40th	-1.2
SID**	Information not available.							
SID-HIII***	168.2	-18.3	27th	-9.8	35.4	-0.7	30th	-2.0
ES-2/2re	159.6	-26.9	18th	-14.4	35.8	-0.3	40th	-0.9
WorldSID-50M	159.5	-27.0	18th	-14.5	34.2	-1.9	8th	-5.4
BIOSID	Information not available.							
BIORID-II	188.8	+2.3	53rd	+1.2	35.0	-1.1	10th	-3.2
MIL-SID	Information not available.							
WIAMan	185	-1.5	50th	-0.8	36.1	0.0	50th	-0.1
PRIMUS	171.5	-15.0	30th	-8.0	36.6	+0.5	65th	+1.3

Note. Dark gray denotes no calculation.

*Value rounded to the nearest percentile.

**The SID ATD is not recommended for impact testing by the International Organization for Standardization.

***The SID-HIII has no shoulder joint for arm attachment.

Table 5. BW and Sitting Heights of the ANSUR II 95M Soldier and 95M Representative ATDs (AFLCMC, 2016; Bartol et al., 1990; Gordon et al., 2014; Humanetics Innovative Solutions, Inc., 2015b)

	Total BW				**Sitting Height**			
Large Males	**Reported BW (lb)**	**Difference from ANSUR II BW (lb)**	**Approximate BW Percentile per ANSUR II***	**PC in BW**	**Reported Sitting Height (in.)**	**Difference from ANSUR II Sitting Height (in.)**	**Approximate Sitting Height Percentile per ANSUR II***	**PC in Sitting Height**
ANSUR II 95M	244.1		95th		38.5		95th	
HIII-95M	223.1	-21.0	86th	-8.6	36.2	-2.3	56th	-5.9
ADAM (Large Male)	217.0	-27.1	83rd	-11.4	37.5	-1.0	83rd	-2.5
LARD	245.0	+0.9	95th	+0.4	38.0	-0.5	90th	-1.2

Note. Dark gray denotes no calculation.
*Value rounded to the nearest percentile.

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ATD Body Mass Distribution, Common Components, and Recommended IARVs

Recommendations for representative ATDs based on male Soldier body mass distribution of body segments as a percentage of BW are reported in Table 6. The recommended male values are compared to the corresponding male ATD body segment mass distribution by occupant size in Table 7 and Table 8. Male ATD body mass distributions were not found for all ATDs reviewed in this report, so these ATDs were removed from the tables. The ATDs not found included the HII, THOR-50M, SID, SID-HIII, BIOSID, ADAM, LARD, and PRIMUS. It should be noted that Soldier-worn PPE was not included in the recommended body mass distribution of body segments.

Table 6. Recommended ATD Body Segment Mass Distribution as a Percentage of BW (TSARP, 1988)

Body Region	Small Male	Mid-Sized Male	Large Male
Head	6.3%	5.1%	4.5%
Neck	1.4%	1.3%	1.2%
Thorax	29.4%	30.5%	31.2%
Abdomen	3.0%	2.9%	3.0%
Pelvis	13.6%	14.5%	14.9%
Upper Arm*	2.4%	2.5%	2.5%
Forearm*	1.7%	1.7%	1.6%
Hand*	0.8%	0.6%	0.6%
Thigh*	12.2%	12.0%	12.1%
Calf*	4.9%	4.7%	4.6%
Foot*	1.3%	1.2%	1.1%

*Value represents one segment and must be doubled for left and right (L/R) sides.

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Table 7. Mid-Sized Male ATD Body Mass Distributions Compared to Recommended Body Mass Distribution as a Percentage of BW (TSARP, 1988; Bartol et al., 1990; Humanetics Innovative Solutions, Inc., 2016a, 2016b, 2017, 2018, 2021; United Nations Economics and Social Council, 2022).

Body Region	**Recommended Mid-Sized Male**	**ADAM (Small Male)**		**HIII-50M**		**FAA-HIII**		**EUROSID-2/re**		**MIL-SID**		**World SID 50M**		**BIORID-II**		**WIAMan****	
		% BM	**PC**	**% BM**	**PC**	**% BM**	**PC**	**% BM**	**PC**	**% BM**	**PC**	**% BM**	**PC**	**% BM**	**PC**	**% BM**	**PC**
Head	5.1	6.6	29.4	5.8	13.7	6.0	17.6	5.5	7.8	5.8	13.7	5.9	15.7	5.3	-17.2	5.3	-17.2
Neck	1.3	1.4	7.7	2.0	53.8	2.0	53.8	1.4	7.7	2.0	53.8	4.0	207.7				
Thorax	30.5	33	8.2	22.1	-27.5	22.8	-25.2	30.9	1.3	30.9	1.3	28.4	-6.9	57.1	19.2	36.3	8.7
Abdomen	2.9	12.4	-28.7	29.7	70.7	23.5	35.1	6.9	137.9	6.9	35.1	26.7	53.4				
Pelvis	14.5							16.6	14.5	16.6						20.8	43.4
Upper Arm*	2.5	2.4	-4.0	2.6	4.0	5.7	18.8	1.8	-28.0	1.8	62.5	2.4	-50.0	4.5	7.1	2.8	12.0
Forearm*	1.7	1.8	5.9	2.2	29.4			NA	NA	NA		NA				1.6	-5.9
Hand*	0.6	0.7	16.7	0.7	16.7			NA	NA	NA		NA		0.7	16.7	0.7	16.7
Thigh*	12	12.3	2.5	7.7	-35.8	17.2	-3.9	17.5	-2.2	***	***	8.1	-32.5	12.2	-26.9	9.0	-25.0
Calf*	4.7	4.9	4.3	5.5	17.0							7.0	18.6			3.4	-27.7
Foot*	1.2	1.2	0.0	1.5	25.0									1.4	16.7	1.3	8.3
Total BW (lb)	**186.5**	**142**	■	**171**	■	**166**	■	**160**	■	***	■	**160**	■	**189**	■	**185**	■

Note. Dark gray denotes no calculation. BM = body mass

*Value represents one segment and must be doubled for the L/R sides.

**WIAMan ATD was based off body segment values from O'Donovan et al. (2013) which reported PMHS percentages.

***MIL-SID is constructed with the HIII-50M head and neck and the ES-2/2re shoulder, arms, upper/lower torso, and upper legs. Total BW and leg weight for MIL-SID was not found.

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Table 8. Large Male ATD Body Mass Distributions Compared to Recommended Body Mass Distribution as a Percentage of BW (Bartol et al., 1990; Humanetics Innovative Solutions, Inc., 2015a; TSARP, 1988)

Body Region	**Recommended Large Male (lb)**	**HIII95M (lb)**	**PC**	**ADAM (Large Male) (lb)**	**PC**
Head	4.5	4.9	-8.9	4.5	0.0
Neck	1.2	1.7	-41.7	1.3	8.3
Thorax	31.2	22.0	29.5	35.2	12.8
Abdomen	3.0	29.9	-67.0	13.6	-24.0
Pelvis	14.9				
Upper Arm*	2.5	2.8	-12.0	2.5	0.0
Forearm*	1.6	2.0	-25.0	1.7	6.2
Hand*	0.6	0.6	0	0.6	0.0
Thigh*	12.1	8.1	33.1	12.0	-0.8
Calf*	4.6	5.7	-23.9	4.6	0.0
Foot*	1.1	1.6	-45.5	1.2	9.1
Total BW (lb)	**244.1**	**223.1**		**245**	

Note. Dark gray denotes that information could not be found.
*Value represents one extremity segment and must be doubled for the L/R sides.

Recommended 50th percentile female Soldier body mass distributions as a percentage of BW were provided by U.S. Army Combat Capabilities Development Command (DEVCOM) Soldier Center (R. Fellin, personal communication, December 15, 2022). Fifth percentile female body mass distribution was not measured directly, and no other studies were found with fifth percentile female information. However, U.S. Army personnel are physically conditioned for the military environment and male body mass distributions showed little differences between percentiles as shown in Table 6. Consequently, the 50th percentile female mass distribution of body segments as a percentage of BW provided were used to compare to the 5F ATD body regions until 5th percentile body mass distribution data become available (Table 9). The recommended 5th percentile female values were compared to the corresponding female ATD mass body segment distribution (Table 10). Body mass distributions were not found for all female ATDs reviewed and those ATDs were removed from the tables. It should be noted that Soldier worn PPE is not included in the recommended body mass distribution of body segments.

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Table 9. Preliminary 50th Female BW as a Percentage of total BW (R. Fellin, personal communication, December 15, 2022)

Body Region	**Preliminary Small Female**
Head	5.5%
Neck	32.4%
Thorax	
Abdomen	21.7%
Pelvis	
Upper Arm*	2.6%
Forearm*	1.3%
Hand*	0.5%
Thigh*	10.3%
Calf*	4.1%
Foot*	1.2%

*Value represents one segment and must be doubled for the L/R sides.

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Table 10. Small Female Body Mass Distributions Compared to Recommended Body Mass Distribution as a Percentage of BW (R. Fellin, personal communication, December 15, 2022, Humanetics Innovative Solutions, Inc., 2020; Humanetics Innovative Solutions, Inc., 2015b).

Body Region	**Preliminary Small Female (lb)**	**HIII-5F (lb)**	**PC**	**SID-IIs (lb)**	**PC**
Head	6.2	8.2	32.0%	8.2	31.2%
Neck	36.6	2.1	-22.2%	2.0	-27.7%
Thorax		26.5		24.5	
Abdomen	24.5	29.2	18.8%	27.6	12.7%
Pelvis					
Upper Arm*	2.9	2.6	-11.9%	2.0	NA
Forearm*	1.5	1.9	32.2%	NA	
Hand*	0.6	0.6	14.6%	NA	
Thigh*	11.6	6.9	-40.7%	6.9	-40.7%
Calf*	4.6	7.2	56.0%	7.2	55.3%
Foot*	1.4	1.7	27.3%	1.7	27.3%
Total BW (lb)	**113.1**	**108.0**	■	**96.0**	■

Note. Dark gray denotes no calculation.
*Value represents one segment and must be doubled for the L/R sides.

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Common and Compatible Components

Common components were identified, and compatibilities of extremities are listed in Table 11. The column titled 'Common Components' indicate the same or similar parts are used in the construction of the ATD. The column titled 'Compatible Components' indicates interchangeable parts that could be used on the specified ATD.

Table 11. Shared and Compatible Components for Reviewed ATDs (AFLCMC, 2016; Humanetics Innovative Solutions, Inc., 2015a, 2015b, 2016a, 2016b, 2017, 2018, 2020, 2021; Humanetics Group, 2023a, 2023b, 2023c, 2023d, 2023e, 2023f, 2023g, 2023h, 2023i; Landolt, 1996; van Ratingen & Bermond, 2003)

ATD	Common Components	Compatible Components
HII	■	■
HIII-5F	■	SAE HIII instrumented arms
HIII-50M	■	HIII lower extremity (LX), THOR-LX, MIL-LX, FOCUS
HIII-95M	■	■
FAA-HIII-50M	Hybrid II: chest flesh, lumbar spine, upper legs Hybrid III: head, neck, rib cage, most upper torso components	HIII-LX, THOR-LX, MIL-LX, FOCUS
THOR-50M	■	HIII-LX, THOR-LX, MIL-LX
THOR-5F	■	■
SID	HII: head, neck, lumbar spine, pelvis, and legs	■
SID-HIII	HIII head, neck, and legs	FOCUS
SID-IIs	■	SAE HIII instrumented arms HIII-5F arms
ES-2	ES modification with unique neck, chest, abdomen, pelvis	■
ES-2re	ES 2 with rib extensions	■
WorldSID-50M	■	■
WorldSID-5F	■	■
BIOSID	HIII head, neck, legs	HIII-LX, THOR-LX, MIL-LX, FOCUS
BIORID-II	■	HIII-50M legs, arms; HIII-LX; THOR-LX; MIL-LX
WIAMan	■	■
ADAM (Small Male)	■	■
ADAM (Large Male)	HIII head and neck	■
LOIS	HIII-5F shoulder (except those made of aluminum), arms, legs	Heads: JSF-SF74A and JSF-SF81H, SAE HIII instrumented arms, HIII-5F legs
LARD	HIII neck, shoulder (clavicle and link changed from aluminum to bronze), arm	Heads: ADAM type head, molded head from HII with ears, JSF-LM110
MIL-SID	ES-2re: shoulders, truncated arms, upper torso, lower torso, upper legs. HIII: head, neck, new lower neck load cell, MIL-LX legs	HIII-LX, THOR-LX, MIL-LX, FOCUS
PRIMUS	■	■

Note. Dark gray denotes that information could not be found.

Impact Direction and Recommended Military IARVs

The ATDs identified in Tables 1 and 2 were reviewed to document the IARVs recommended for the military environment and corresponding impact direction (Table 12 and Table 13). Recommendations from "The Critical Review of Injury Assessment Reference Values for Application in the Military Environment," Volumes I and II, were made for IARVs applicable to military impact events and the ATD used in matched-pair testing (Rhodes et al., 2022a; Rhodes et al., 2022b). Volume 1 reviewed IARVs for the head, neck, chest, spine, abdomen, and pelvis, and Volume II reviewed IARVs for the upper and lower extremities. The recommended IARVs are located in Tables B1 and B2. The validated ATDs recommended by Rhodes et al. (2022a, 2022b) were commonly used in the civilian automotive environment except for the WIAMan ATD, which was developed for ground vehicle UBB scenarios. The U.S. Air Force uses the LOIS, LARD, and ADAM for ejection seat testing, each of which have IARVs specific to them.

Table 12. Whole-Body ATDs with Corresponding Impact Direction and Source of Recommended IARVs

ATD	Impact Direction with Recommended IARVs	References for Recommended Military IARVs
HII	AP	None
HIII-5F		Rhodes et al., 2022a
HIII-50M		Rhodes et al., 2022a
HIII-95M		Rhodes et al., 2022a
THOR-50M		Rhodes et al., 2022a
THOR-5F		None
SID	Lateral	None
SID-HIII		Rhodes et al., 2022a
SID-IIs		Rhodes et al., 2022a
ES-2		Rhodes et al., 2022a
ES-2re		Rhodes et al., 2022a
WorldSID-50M		None
WorldSID-5F		None
BIOSID		Rhodes et al., 2022a
MIL-SID		Rhodes et al., 2022a
BIORID-II	PA	None
FAA-HIII	Vertical	Rhodes et al., 2022a
HIII-50M		Rhodes et al., 2022a
WIAMan		None*
ADAM (Small Male)		Bartol et al., 1990
ADAM (Large Male)		Bartol et al., 1990
LOIS		AFLCMC, 2016
LARD		AFLCMC, 2016
PRIMUS	In Development	In Development

*At the time of this report, IARV development for WIAMan is still ongoing.

Table 13. ATD Accessories with Corresponding Validated Impact Direction and Source of Recommended IARVs

Alternate ATD Accessories	**Validated Impact Direction**	**References for Recommended Military IARVs**
HIII-50M Instrumented Arm	AP, Lateral	None
SAE HIII-5F Instrumented Arm	Any exposure that may induce upper extremity flail	Rhodes et al., 2022b
HIII-LX Legform (All Percentiles)*	AP	None
THOR-LX*	AP	None
MIL-LX*	Vertical	None
FOCUS Headform	AP, Lateral	Rhodes et al., 2022a

*Lower extremities (LX) only include the tibia/fibula, ankle, and foot.

Summary of the Data

Summary tables of the whole-body ATDs and the criteria for selecting applicability to the military environment by impact direction are shown in Table 14 to Table 17. Criteria included anthropometry (BW and sitting height) with green denoting within a 10% deviation, yellow denoting between 10% and 20% deviation, and red denoting a greater than 20% deviation from the recommended values of ANSUR II (Gordon et al., 2014). The same denotation was used for the comparison of body mass distribution recommended in TSARP (1988) and DEVCOM Soldier Center (R. Fellin, personal communication, December 15, 2022). Also noted was the presence of a full or truncated arm and if there were recommended IARVs for the impact direction.

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Table 14. Whole-Body ATD Applicability for AP Impacts

ATD	Anthropometry		% Body Mass Distribution					Full/ Segmented Arm	Recommended IARVs
	BW	Sitting Height	Head and Neck	Thorax	Abdomen and Pelvis	Arm*	Leg*		
HII-50M	🟨	🟩	⬛	⬛	⬛	⬛	⬛	Full	None
HIII-5F	🟩	🟩	🟥	🟥	🟨	🟨	🟨	Full	✓
HIII-50M	🟩	🟩	🟥	🟥	🟥	🟨	🟨	Full	✓
HIII-95M	🟩	🟩	🟨	🟥	🟥	🟨	🟨	Full	✓
FAA-HIII**	🟨	🟩	🟥	🟥	🟥	🟨	🟩	Full	✓
THOR-5F	🟩	🟩	⬛	⬛	⬛	⬛	⬛	Full	None
THOR-50M	🟩	🟩	⬛	⬛	⬛	⬛	⬛	Full	✓
PRIMUS	🟩	🟩	⬛	⬛	⬛	⬛	⬛	Full	None

Note 1. Green denotes < 10% deviation, yellow denotes between 10 and 20% deviation, and red denotes > 20% deviation from recommended values.

Note 2. Dark gray denotes information could not be found.

*Arms and legs are inclusive of the entire limb.

**FAA-HIII shares components with the HIII-50M which have recommended IARVs for AP impacts.

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Table 15. Whole-Body ATD Applicability for Lateral Impacts

ATD	**Anthropometry**		**% Body Mass Distribution**					**Full/ Segmented Arm**	**Recommended IARVs**
	BW	**Sitting Height**	**Head and Neck**	**Thorax**	**Abdomen and Pelvis**	**Arm***	**Leg***		
SID-IIs	🟨	🟩	🟥	🟨	🟨	⬛	🟥	Half**	✓
SID-HIII	🟩	🟩	⬛	⬛	⬛	⬛	⬛	⬛	✓
ES-2/2re	🟨	🟩	🟩	🟩	🟥	⬛	🟩	Half	✓
WorldSID-5F	🟩	🟩	⬛	⬛	⬛	⬛	⬛	Half	None
WorldSID-50M	🟨	🟩	🟥	🟩	🟥	⬛	🟨	Half	None
BIOSID	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	✓
MIL-SID	⬛	🟩	🟥	🟩	🟥	⬛	⬛	⬛	✓

Note. Green denotes < 10% deviation, yellow denotes between 10% and 20% deviation, and red denotes > 20% deviation from recommended values.

Note. Dark gray denotes information that could not be found.

*Arms and legs are inclusive of the entire limb.

**Full arm when used with the SAE HIII 5th Instrumented Arm.

Table 16. Whole-Body ATD Applicability for Rear Impacts

ATD	**Anthropometry**		**% Body Mass Distribution**					**Full/ Segmented Arm**	**Recommended IARVs**
	BW	**Sitting Height**	**Head and Neck**	**Thorax**	**Abdomen and Pelvis**	**Arm***	**Leg***		
BIORID-II	🟩	🟩	🟨	🟨	🟨	🟩	🟥	Full	None

Note 1. Green denotes < 10% deviation, yellow denotes between 10% and 20% deviation, and red denotes > 20% deviation from recommended values.

*Arms and legs are inclusive of the entire limb.

Table 17. Whole-Body ATD Applicability for Vertical Impacts

ATD	Anthropometry		% Body Mass Distribution					Full/ Segmented Arm	Recommended IARVs
	BW	Sitting Height	Head and Neck	Thorax	Abdomen and Pelvis	Arm[*]	Leg[*]		
ADAM (small)	🟥	🟩	🟥	🟩	🟥	🟩	🟩	Full	✓[**]
ADAM (large)	🟨	🟩	🟩	🟨	🟥	🟩	🟩	Full	✓[**]
LOIS	🟩	🟩	⬛	⬛	⬛	⬛	⬛	Full	✓[**]
LARD	🟩	🟩	⬛	⬛	⬛	⬛	⬛	Full	✓[**]
WIAMan	🟩	🟩	🟨	🟨		🟩	🟥	Full	None
HIII-50M	🟩	🟩	🟥	🟥		🟨	🟨	Full	✓
FAA-HIII	🟨	🟩	🟥	🟥	🟥	🟨	🟩	Full	✓

Note 1. Green denotes < 10% deviation, yellow denotes between 10% and 20% deviation, and red denotes > 20% deviation from recommended values.

Note 2. Dark gray denotes information could not be found.

[*] Arms and legs are inclusive of the entire limb.

[**] Ejection seat testing only.

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Seat orientations can vary in military ground and air vehicles. The military environment can also include scenarios where the vehicle is impacted in the forward, lateral, rear, and vertical directions. A schematic of potential vehicle occupant seat orientations and vehicle impact directions is illustrated in the Figure to help determine which ATD is appropriate for the research being conducted. Once the seating orientation and vehicle loading direction to be tested is selected, ATD recommendations based on seating orientation, primary impact direction use, injury risk (if IARVs are recommended for the military environment) or comparative assessment, and loading type (contact or inertial) in Table 18 and Table 19 can be used.

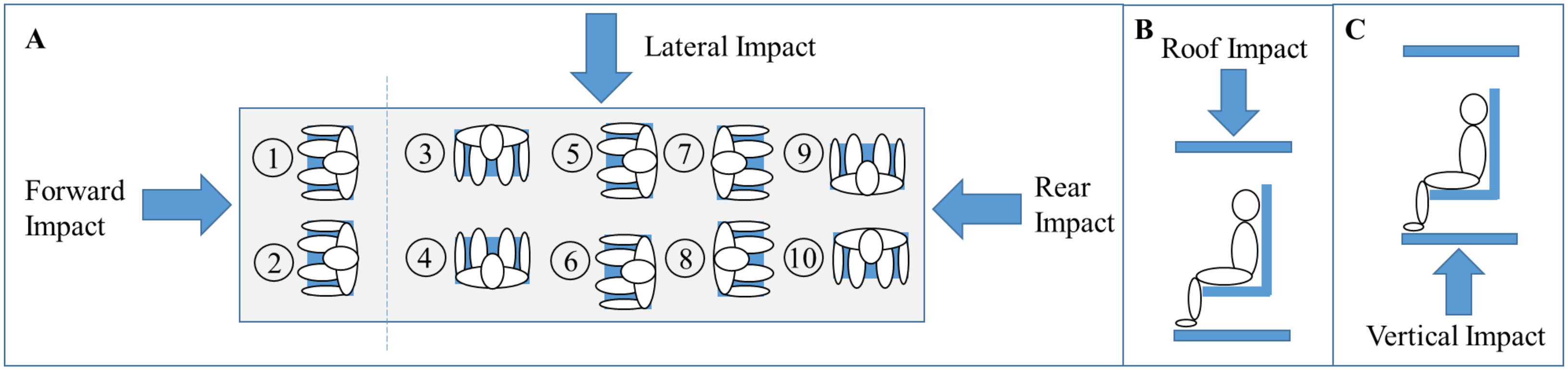

Figure 1. Potential occupant seat orientations and vehicle impact directions for ground and air military vehicles.

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Table 18. Summary and Whole-Body ATD Recommendations for Forward and Lateral Vehicle Impact Directions

Vehicle Impact Direction	Seating Position	Objective		Loading		Recommended ATD	Available Sizes	Available Sensor Channels
		Injury Risk Assessment	Comparative Assessment	Contact	Inertia (Upper Extremity Flail)			
Forward	1, 2, 5, 6	X	X	X	X	HIII	5F 50M 95M	50+
	1, 2, 5, 6		X	X	X	THOR	5F 50M	100+
	3, 4, 9, 10	X	X	X		SID-IIs ES-2/2re	5F 50M	100+ 80+
	7, 8		X	X	X	HIII	5F 50M 95M	50+
Lateral	1, 2, 5, 6, 7, 8	X	X	X		SID-IIs ES-2/2re	5F 50M	100+ 80+
	3, 10		X	X	X	HIII	5F 50M 95M	50+
	4, 9	X	X	X	X	HIII	5F 50M 95M	50+
	4, 9		X	X	X	THOR	5F 50M	100+

Table 19. Summary and Whole-Body ATD Recommendations for PA and Vertical Vehicle Impact Directions

Vehicle Impact Direction	Seating Position	Objective		Loading		Recommended ATD	Available Sizes	Available Sensors Channels
		Injury Risk Assessment	Comparative Assessment	Contact	Inertia (Upper Extremity Flail)			
Rear	1, 2, 5, 6		X	X	X	HIII	5F 50M 95M	50+
	3, 4, 9, 10	X	X	X		SID-IIs ES-2/2re	5F 50M	100+ 80+
	7, 8	X	X	X	X	HIII	5F 50M 95M	50+
	7, 8		X	X	X	THOR	5F 50M	100+
Vertical (B and C)	ALL	X	X	X	X	HIII	5F** 50M 95M**	50+
		X				FAA-HIII	50M	
		***				WIAMan	50M	150+

*For comparative assessments in rear facing seats, HIII-5F, 50M, and 95M can potentially be used.

**HIII-5F and HIII-95M IARV development is currently underway at USAARL.

***IARV development for WIAMan is currently underway.

Discussion

Most ATDs were designed for use in the civilian automotive environment. While military air and ground vehicles can experience impact events that are similar to civilian events, the military environment can be more complex. Military ground vehicles can be exposed to UBB loading conditions. The variability of seat orientation in military air and ground vehicles can expose the occupants to different loading directions. The extensive use of PPE by military personnel, not worn in civilian environments, introduces another variable to be addressed when testing with ATDs to determine injury risk and crash survival. Additionally, military combat vehicles are ruggedly designed to withstand the structural demands of harsh combat environments and are designed for quick loading and unloading of passengers. Military combat vehicle structures are often designed for protection from kinetic threats and occupant compartments lack energy mitigation features common in civilian vehicles; consequently, high acceleration levels at high onset rates may be transmitted during dynamic military events. Occupants of these vehicles, who may not be optimally restrained, often experience flail of the head/neck, torso, and extremities onto rigid structures specific to the military vehicles, which are not commonly assessed by the automotive industry. The ability of ATDs to correctly mimic occupant response during military events is influenced by ATD anthropometry, such as BW, sitting height, body mass distribution, a full or segmented arm, and the use of military PPE and combat equipment. Additionally, not all developed IARVs may be appropriate for the military environment. IARVs must be developed for operationally relevant military exposures using an ATD that is validated for the impact direction tested. The IARVs identified in Rhodes et al. (2022a, 2022b) were recommended for use with their respective ATD for military scenarios.

Occupant BW and sitting height play an important role in assessing injury risk and equipment performance during military vehicle impacts. Kinematics and occupant response loads are affected by the total mass of the occupant with donned equipment and the mass distribution. Military design standards, such as MIL-S-85510 and MIL-S-58095 (AV), that define rotary-wing seat performance requirements for occupant safety, use the combined occupant BWs and seat weight to determine seat static and dynamic strength requirements (DoD, 1981; DoD, 1986). Rhodes et al. (2021) determined that the total BW of the Soldier and their equipment had increased since the standards were released. Gordon et al. (2014) reported Soldier BW and sitting height measurements for many percentiles of the population including the 5th, 50th, and 95th percentiles. The results of the Gordon et al. (2014) study were compared to 23 ATDs for this report. While most ATDs had sitting heights consistent with the Gordon et al. (2014) values, the BWs of many ATDs were lower than the U.S. Army population for the 5F, 50M, and 95M groups. The largest differences were noted in the ATDs that are representative of the 50M and 95M. The 50M ATDs were found to be between 10 and 44 lb lighter than their associated Soldier percentile, while the 95M ATDs were found to be between 20 and 30 lb lighter than their reported Soldier percentile. These weights do not include Soldier worn equipment weight (PPE and combat equipment) that contribute to seat strength requirements.

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Additionally, to accurately assess occupant safety and avoid errors in injury assessments, the ATD body mass distribution should be representative of the respective Soldier population and the ATD anthropometry should accommodate Soldier worn equipment. In dynamic tests, inaccurate ATD body mass distributions (e.g., torso, head, extremities) can influence the ATD flail and its resulting impact strikes and sensor readings, that in turn can lead to an inaccurate injury risk assessment. It should be noted that the differences in body mass distribution could influence the occupant kinematics and sensor readings, depending on mass location, and result in inaccurate injury risk assessments. This report also did not consider the center of mass location of each body region/segment, which will also affect occupant kinematic response.

The inclusion of PPE on an ATD during dynamic testing can also influence ATD response kinematics and the resulting injury risk assessment. The weight addition from PPE can influence the ATD flail response. By design, PPE, such as a rotary-wing flight helmet, is intended to protect the wearer and as such may absorb impact energies and distribute the impact points over greater surface areas. PPE such as torso body armor vests, could provide external support to the torso, distribute the shoulder harness restraint forces across larger body areas, and reduce flail. Coupling of PPE to the body varies, as its mass could be additive to the body or could be independent (i.e., PPE can be strapped tightly or loosely to the body). The effect of PPE use is also influenced by its sizing compatibility and fit onto the ATD. Use of a protective helmet with the HIII-50M is difficult as the HIII-50M headform was designed to provide repeatable results in automotive car crash tests and not to accommodate helmets. Helmet fit and retention on the HIII-50M headform is poor and can influence test results. Thus, the effects of PPE use may alter the observed flail response and influence the ATD sensor measurements. Implications of PPE use on ATDs in dynamic testing are not well established and should be further investigated.

Inclusion of PPE during ATD dynamic testing should be deliberate based on the intent of the test. An example case is the dynamic testing of crashworthy seats, which are designed to stroke and absorb some of the impact energy. In this case, since Soldiers will be required to wear the PPE, the seat performance needs to accommodate the mass increase due to the PPE. However, if a seat performance requirement is to limit the peak force measured in the ATD lumbar load cell, then the mass of PPE worn above the load cell will likely increase the measured forces. Finally, the use of additional ballasts to artificially weight the ATD to meet a weight requirement for a dynamic test should be avoided because use will alter the ATD mass distribution and influence the ATD flail response and sensor measurements.

ATD instrumentation includes load cells, accelerometers, angular rate sensors, etc. to measure the ATD response to an event. As the number of sensors required for a test increases, the cost per test increases. This is related to the cost of instrumenting and calibrating the ATD, increased cost associated with multi-channel data acquisition systems, and increased data analyst hours needed to post-process and analyze the increased number of data channels.

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Some ATD designs may not be appropriate for dynamic military tests and their use could result in inaccurate injury risk assessments. The geometry of the ATD heads may not permit the appropriate retention of a helmet to its head resulting in inaccurate head and neck injury risk assessments. Additionally, the lack of a full arm in side impact ATDs prohibits the assessment of upper extremity flail; therefore, ATDs with partial arms can only be used to evaluate contact loads. All of the automotive side impact dummies are intended to assess door intrusion injury risk and occupy the impact side (near side) of an automotive side impact test. The assessment of upper torso and extremity flail is especially important for the evaluation of seat restraint systems in a longitudinal rotary-wing impact when the seat is mounted in the side facing position. Current testing requirements and ATD recommendations for side facing seat performance and restraints is limited.

Understanding the capabilities and limitations of different available ATD designs allows researchers and materiel developers to choose the ATD that best matches the intended application and promotes confidence for collecting accurate test results for performance and injury risk interpretation. Recommended IARVs are associated with ATDs by body region and their specific components, and many ATDs share components. It is recommended that researchers who use ATDs containing these common components implement the IARVs with the guidance given by Rhodes et al. (2022a, 2022b) while noting the ATD advantages and limitations. Rhodes et al. (2022a, 2022b) recommended the ATD specific IARVs that are applicable for use in military environments, specifically for U.S. Army air and ground vehicles. The U.S. Air Force also made recommendations for ADAM, LOIS, and LARD, but these only pertain to the ejection seat environment (AFLCMC, 2016). It is imperative that researchers select appropriate ATDs specific to the application and consider both the anthropometry of the occupants and the military equipment and PPE they wear.

Recommended IARVs for specific impacts consistent with military events are required for injury risk assessment; therefore, not all data can be used to determine injury risk. Until injury criteria are validated and matched-pair tested with the appropriate ATD, only comparative assessments from sensor responses should be used to evaluate military materiel. Additionally, IARVs are influenced by the biofidelity of the ATD; however, an in-depth biofidelity study of the ATDs reviewed was outside the scope of this report due to the breadth of review needed.

Twenty-three standard ATDs and five extremities were reviewed during this study to determine their applicability when assessing injuries that occur in the military environment. Available figures and instrumentation of each ATD reviewed can be found in Appendix A.

HII-50M

The HII-50M deviated less than 10 % in BW and 10%–15% in sitting height than the reported values in ANSUR II (Gordon et al., 2014). Body mass distributions are not reported for this ATD, so it is unclear if the HII would respond appropriately during a crash or dynamic event. This HII-50M ATD design was the predecessor to the HIII and is considered obsolete. However, the HII head anthropometry and its facial features do provide desirable compatibility with military helmets.

HIII-5F, 50M, and 95M

The BW and sitting height of the HIII-5F, 50M, and 95M deviated less than 10% of the reported values in ANSUR II (Gordon et al., 2014). Large differences in BM distributions were also noted in the head, neck/thorax, abdomen/pelvis, and thigh; some deviating over 20% from the recommended values. All sizes have full arms to assess upper extremity flail for comparative assessment. The HIII-5F, 50M, and 95M have recommended IARVs to assess injury risk in military scenarios and can also be used for comparative assessment (Rhodes et al., 2022a). The HIII-5F, 50M, and 95M are recommended for use in the military environment for the AP impact direction. The HIII-50M is also recommended for use in the military environment in the vertical direction.

THOR-5F and 50M

The BW and sitting height of the THOR-5F and 50M deviated less than 10% of the reported values in AUSUR II (Gordon et al., 2014). The BM distribution needed for assessing injury and occupant kinematics could not be found for the THOR. Both sizes have full arms to assess upper extremity flail for comparative assessment. The THOR-50M and the newer 5F ATDs have been in continuous refinement during validation by the NHTSA for use in AP impact tests. Rhodes et al. (2022a) only reported one IARV valid for the military environment for the THOR-50M ATD. The THOR-5F and 50M is only recommended for comparative assessments in the AP impact direction until IARVs are developed.

SID

The BW, sitting height, and BM distribution needed for assessing injury and occupant kinematics could not be found for the SID-HIII ATD. The SID is considered obsolete and is not recommended by the International Organization for Standardization; consequently, it is not recommended for testing military impact events in military ground and air vehicles.

SID-IIs

The SID-IIs BW deviated between 10%–15% and sitting height deviated less than 10% from the reported values for the 5F in ANSUR II (Gordon et al., 2014). Deviations in BM distribution of about 30% were noted in the head/neck and thorax, and 10%–15% in the abdomen/pelvis from the recommended values (TSARP, 1988). The differences in body mass distribution will affect ATD kinematics in an impact event and the ability to accurately assess injury risk due to flail. IARVs for lateral impacts are recommended for the military environment and their shared and compatible components should be followed (Rhodes et al., 2022a). The SID-IIs has a truncated arm installed on the side of impact and therefore would not be able to assess upper extremity flail. The SID-IIs is recommended for the small female for injury and comparative assessments in lateral impacts.

SID-HIII

The SID-HIII BW and sitting height deviated less than 10% from the reported values in ANSUR II (Gordon, et al., 2014). BM distribution needs to assess injury and occupant kinematics could not be found for the SID-HIII. In addition, the SID-HIII does not have a shoulder joint for the installation of upper extremities. Although the SID-HIII has recommended IARVs for lateral impacts (Rhodes et al., 2022a), it would not be possible to evaluate PPE such as body armor or restraint systems without upper extremities. Therefore, the SID-HIII is not recommended for the military environment.

ES-2 and ES-2re

The ES-2/2re BW deviated between 10%–15% from the reported values in ANSUR II (Gordon et al., 2014). Sitting height deviated less than 10%. BM distribution deviated less than 10% from recommendations (TSARP, 1988), with the exception of the abdomen and pelvis. The ES-2/2re have a truncated arm that would prevent an accurate assessment of upper extremity flail. The ES-2/2re have recommended IARVs in lateral impacts and are recommended for use in the military environment (Rhodes et al., 2022a).

WorldSID-5F and 50M

The WorldSID-5F BW and sitting height deviated less than 10% from the reported values in ANSUR II (Gordon et al., 2014). The BM distribution for the WorldSID-5F could not be found and should be considered when assessing injury and occupant kinematics. Additionally, the WorldSID-5F was scaled from the 50M, which may not accurately assess female Soldier anthropometry. The WorldSID-5F has a truncated arm that would prevent an accurate assessment of upper extremity flail. There are also no recommended IARVs associated with this ATD for the military environment (Rhodes et al., 2022a), and it is unclear how the WorldSID-5F would respond to military exposures. Further research is necessary to evaluate the WorldSID-5F response to military exposures.

The WorldSID-50M BW deviated 10%–15% and sitting height deviated less than 10% from the reported values in ANSUR II (Gordon et al., 2014). The BM distributions of the head/neck and abdomen/pelvis deviated over 20% from the recommended values (TSARP, 1988). The differences in total BW and body mass distribution could influence the ATD kinematics in an impact event, and the ability to accurately assess injury risk due to flail. The WorldSID-50M has a truncated arm that would prevent an accurate assessment of upper extremity flail. There are also no recommended IARVs associated with this ATD for the military environment (Rhodes et al., 2022a), and it is unclear how the WorldSID-50M would respond to military exposures. Further research is necessary to evaluate the WorldSID-50M response to military exposures.

BIOSID

Anthropometry and BM distribution could not be found for this ATD and should be documented to compare with the 50M Soldier population. Differences in anthropometry and BM distribution will affect the ATD kinematics in an impact event and the ability to accurately assess injury risk due to flail. The BIOSID has recommended IARVs in lateral impacts (Rhodes et al., 2022a); however, the BIOSID is not recommended for the military environment until anthropometry and BM distributions are assessed.

MIL-SID

The MIL-SID BW could not be determined because it is commercially sold as just the torso, abdomen, and pelvis with truncated arms. The sitting height (with the HIII head and neck) deviated less than 10% from the reported values in ANSUR II (Gordon et al., 2014). The BM distributions of the head/neck and abdomen/pelvis deviated over 20% from the recommended values (TSARP, 1988). The differences in total BW and body mass distribution could influence the ATD kinematics in an impact event and the ability to accurately assess injury risk due to flail. The MIL-SID has truncated arms that would prevent an accurate assessment of upper extremity flail. The MIL-SID is capable of assessing lateral and vertical forces. The MIL-SID shares components with the HIII (head/neck) and ES-2/2re shoulders, truncated arms, upper torso, lower torso, and upper legs, and therefore, shared recommended IARVs. The MIL-SID is recommended for injury assessment and comparative assessments in the military environment.

BIORID-II

The BIORID-II total BW and sitting height deviated less than 10% from the reported values in ANSUR II (Gordon et al., 2014). The BM distribution for all regions deviated between 10%–15% from the recommended values (TSARP, 1988). However, this ATD was designed and developed to assess occupant whiplash risk when impacted from the PA direction. Validation testing was conducted with volunteers in low impact exposures, therefore, the IARVs associated with this ATD were not recommended by Rhodes et al. (2022a). The BIORID-II is not recommended to assess injury in military impact events in U.S. Army air/ground vehicles without further validation.

ADAM

The BW and BM used to design both ADAMs (small and large male) are lower than the 50M and 95M Soldier populations (Gordon et al., 2014; TSARP, 1988). The difference in anthropometry could be due to the differences in U.S. Army versus Air Force personnel. The ADAM (small and large male) was designed for the ejection environment, and the ATD biofidelity and dynamic response to other military impact scenarios are unknown. There are also no validated IARVs for military impact events other than aircraft ejection, and therefore, the ADAM is not recommended for injury risk assessment for military environments in non-ejection scenarios.

LOIS and LARD

The LOIS and LARD total BW and sitting heights deviated less than 10% from the reported values in ANSUR II (Gordon et al., 2014). The difference in anthropometry could be due to the differences in U.S. Army versus Air Force personnel. Body mass distribution for the LOIS and LARD could not be found and should be considered when assessing injury and occupant kinematics. There are also no validated IARVs for military impact events other than aircraft ejection, and therefore, the LOIS and LARD are not recommended for injury risk assessment for military environments in non-ejection scenarios.

WIAMan

The WIAMan total BW and sitting height deviated less than 10% from the reported values in ANSUR II (Gordon et al., 2014). The BM distribution for all regions, except the leg, deviated between 10%–15% from the recommended values (TSARP, 1988) and WIAMAN has full arms to assess upper extremity flail for comparative assessment. The WIAMan ATD was developed by the U.S. Army to evaluate injury risk during ground vehicle UBB exposures. Its biofidelity and dynamic response to other military impact scenarios are unknown. While there are many sensors, only a small percentage of sensors have been validated with matched-pair testing. Most testing has been related to vertical loading of the lumbar spine, pelvis, and lower extremity (mainly the foot and lower leg), but the risk of injury must be defined to find the associated IARV. Most of the data collected are in vertical loading conditions with little to no data in the non-vertical environment. Also, the development of the WIAMan included matched-pair testing with PMHS that were donned with the then-standard issue combat boots, helmets, combat vests, and body armor (circa 2010–2015). It is unclear how the PMHS tests were influenced by the performance of that PPE. The boot tested in the development of WIAMan is no longer standard issue, and testing with current, newly designed boots, may alter the load transferred to the leg. Therefore, WIAMan is not recommended for injury risk assessment for military environments without additional matched-pair testing with PMHS sans boots.

FAA-HIII-50M

The FAA-HIII total BW deviated 10%–15% and sitting height deviated less than 10% from the reported values in ANSUR II (Gordon et al. 2014). The BM distribution for the head/neck, thorax, abdomen/pelvis deviated over 20% from the recommended values (TSARP, 1988). The FAA-HIII has full arms to assess upper extremity flail for comparative assessment. The differences in sitting height, total weight, and body mass distribution will affect the ATD kinematics in an impact event and the ability to accurately assess injury risk due to flail. The FAA-HII is recommended for injury assessment of the lumbar region during vertical loading of the lumbar region (Humanetics Group, 2021). The FAA-HIII is recommended for vertical impacts with recommended IARVs in the military environment.

PRIMUS

The PRIMUS total BW and sitting height deviated less than 10% from the reported values in ANSUR II (Gordon et al., 2014). Body mass distribution for PRIMUS could not be found and should be considered when assessing injury and occupant kinematics. There are also no validated IARVs for military impact events (Table 12). The PRIMUS is not recommended to assess injury in military impact events in U.S. Army air or ground vehicles without further validation.

HIII Instrumented Arm for 50M

The BM distribution of the HIII Instrumented Arm for 50M is consistent with TSARP (1988) recommendations. The HIII-50M Instrumented Arm does not have recommended IARVs for the miliary environment and should only be used for comparative assessment. It is recommended that matched-pair testing be conducted on PMHS and the HIII-50M upper extremity to validate IARVs in military events.

SAE HIII-5F Instrumented Arm

The SAE International instrumented arms are compatible with the SID-IIs and the HIII-5F and is recommended for use in military impact events where the upper extremities flail and may cause hyperextension of the elbow (Rhodes et al., 2022b). It is recommended that the SID-IIs be used to assess the small female population in lateral impacts with IARVs recommended (Rhodes et al., 2022b). The SAE HIII-5F instrumented arm has recommended IARVs for the military environment and can be used to assess injury risk.

HIII-LX

Standard HIII ATDs have instrumented LX legforms; however, the lower leg load cells were designed for through-the-foot loadings from floor intrusion during frontal car impacts. Because of the rigid structure of the lower leg, the instrumentation maximum range may be inadequate for the loading conditions of some military scenarios.

THOR-LX Advanced Legform

Although the THOR-LX Legform was found to exhibit greater biofidelity than the HIII-LX Legform (Rudd et al., 2000), there are no recommended IARVs for the military environment (Rhodes et al., 2022b). It is recommended that matched-pair testing be conducted on PMHS and the THOR-LX to validate IARVs in military events. The THOR-LX Legform should be used for comparative assessments only.

MIL-LX Legform

The MIL-LX may be more appropriate for testing with higher input loads like UBBs. The MIL-LX incorporates a compliance element and new load cell to assess injury risk of antipersonnel land mine explosions with different boot designs. The MIL-LX Legforms have also shown better biofidelity than the HIII-50M lower leg; however, there are no recommended IARVs for the military environment (Rhodes et al., 2022b). It is recommended that matched-pair testing be conducted on PMHS and the MIL-LX to validate IARVs in military events. The MIL-LX Legform should be used for comparative assessments only.

FOCUS Headform

The FOCUS headform is recommended for the military environment. Mandible injury criteria was published by Daniel et al. (2021); however, IARV development for other facial bones is still ongoing. The recommended reference and impact direction cited in Rhodes et al. (2022a) should be followed to assess injury in the military environment with the compatible ATDs of the headform (Table 10).

Conclusion and Recommendations

Anthropometry and body mass distributions of the representative population are critical parameters in ATD design as they directly affect inertial body flail and contribute to risk of contact during flail. Thus, they are important for the accurate assessment of injury risk. If the ATD (as a whole) or body region is improperly sized, then the loading, flail trajectories, and sensor measurements will be influenced.

The ATD body mass distributions will affect occupant kinematics and sensor readings during impact. This becomes especially important as new seat designs with recline features are suggested. It is recommended that matched-pair testing be conducted to understand how seating position affects occupant kinematics, alignment with respect to impact, and IARV development.

Analysis of the center of mass locations for each body segment was not included in this report. It is recommended that the center of mass and mass properties for each body region/segment be determined for the Soldier population and compared to the existing ATD body segments. These center of mass locations and mass properties values can then be used for ATD design and development efforts.

Current ATDs and their corresponding IARVs are not inclusive of PPE use (Rhodes et al., 2022a). To properly represent a dynamic military environment, the ATD must properly accommodate military PPE expected to be worn by Soldiers in the environment. It is unclear how the use and presence of PPE will influence sensor measurements and flail trajectories. It is recommended that matched-pair testing be conducted with PPE to determine differences in sensor measurement and flail.

The side impact ATDs often do not come with two full arms. Absence of the lower arm will alter the flail trajectory of the upper extremity. To accurately assess flail during impact, two full and correctly weighted arms are needed to calculate flail trajectories. It is recommended that more work be conducted to develop upper and lower extremities for male and female Soldier populations.

The IARVs for side impact ATDs are limited. It is recommended that side facing seats and ATDs should be evaluated in longitudinal vehicle impacts to assess injury risk.

ATD Recommendations for the AP Impact Direction

The HIII-5F, 50M, and 95M are recommended for use in studying AP impacts for injury risk and comparative assessments; however, flail assessments should be approached with caution due to the body mass distributions deviating by more than 20% of the recommended values in multiple body regions. Reference recommendations are reported in Table 18 and 19. Recommended IARVs from Rhodes et al. (2022a, 2022b) are reproduced in Table B1 and B2.

Currently, the THOR-50M has only one IARV recommended for the military environment for AP impacts. It is recommended that the THOR-5F and 50M should be used for comparative testing until IARVs are developed. Reference recommendations are reported in Table 18 and 19. Recommended IARVs from Rhodes et al. (2022a, 2022b) are reproduced in Appendix Table B1 and B2.

ATD Recommendations for the Lateral Impact Direction

The SID-II is recommended for lateral impacts with the SAE HIII 5th Instrumented Arms; however, more testing is needed to develop IARVs for the military environment for other body regions. Flail assessment should also be approached with caution due to the head/neck and abdomen/pelvis mass distributions deviating over 20% from the recommended values in multiple body regions. Reference recommendations are reported in Table 18 and 19. Recommended IARVs from Rhodes et al. (2022a, 2022b) are reproduced in Appendix Table B1 and B2.

The ES-2/2re BW, sitting height, and body mass distributions are within 10% of the recommended values (except for BW being within 15%), which would make this ATD a good candidate for testing in the military environment. There are recommended IARVs for lateral impacts applicable to the military environment; however, due to the ES-2/2re segmented arm, flail of the upper and lower extremities cannot be studied. It is recommended that more testing be conducted to assess injury for the military environment. Reference recommendations are reported in Table 18 and 19. Recommended IARVs from Rhodes et al. (2022a, 2022b) are reproduced in Appendix Table B1 and B2.

The MIL-SID is recommended for injury assessment and comparative assessments in the military environment. The MIL-SID shares components with the HIII (head/neck) and ES-2/2re shoulders, truncated arms, torso, abdomen/pelvis, and upper legs, and therefore share recommended IARVs. Recommended IARVs from Rhodes et al. (2022a, 2022b) are reproduced in Appendix Table B1 and B2.

ATD Recommendations for the PA Impact Direction

There were no ATDs with IARVs in PA impacts recommended for the military environment; however, anthropometry and availability of the HIII-5F, 50M, and 95M would allow for their use in rearward loading conditions for comparative assessments only. However, more work is needed to properly assess their rearward biofidelity performance as well as that of other potential ATDs (THOR, WIAMan, etc.).

The BIORID-II, developed to assess whiplash risk, has anthropometry and body mass distribution less than 10% and between 10% and 20% of the recommended values, respectively. It is recommended that additional testing be conducted with the BIORID-II to develop IARVs to assess whiplash risk in PA impacts for the military environment.

ATD Recommendations for Vertical Impact

The HIII-50M and the FAA-HIII both have IARVs recommended for the military environment for vertical impact. Flail assessment should be approached with caution because body mass distributions are over 20% of the recommended values in multiple body regions. Reference recommendations are reported in Table 18 and 19. Recommended IARVs from Rhodes et al. (2022a, 2022b) are reproduced in Appendix Table B1 and B2.

To date, the HIII-5F, HIII-95M, THOR-5F, and THOR-50M ATDs do not have recommended IARVs for the military environment in vertical impacts. The USAARL is currently developing IARVs for the HIII-5F and HIII-95M for potential use in rotary-wing seat energy attenuation assessments until improved ATD designs emerge. More testing to develop IARVs with THOR-5F and 50M for vertical impact testing is recommended.

The WIAMan ATD was designed specifically for vertical UBB impacts in the military environment; however, most IARV development has been on the lower extremities and to-date, the IARVs have not been finalized. The IARV development is ongoing, and it is recommended that researchers review forthcoming literature for updates as more information becomes available.

Extremity Recommendations

The FOCUS headform has IARVs validated for the military environment and is compatible with the HIII-50M and FAA-HIII. The FOCUS headform also has anthropometric and facial features which make it more compatible with military headgear and head-mounted devices. Therefore, FOCUS is recommended for use in conjunction with HIII-50M and FAA-HIII to assess facial injuries where AP and lateral impacts may occur.

The SAE HIII-5F Instrumented Arm is recommended for the military environment for injury and comparative assessments.

The MIL-LX and THOR-LX Advanced Legforms are recommended for the military environment for comparative assessments.

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Appendix A. Anthropomorphic Test Devices (ATDs) and Instrumentation

This section provides a schematic and an instrumentation table for the ATDs presented in this report. Shaded boxes indicate no further instrumentation. Values followed by an 'X' indicate the number of sensors (for example: 3X F_x load cells means three uni-axial [F_x] load cells). InfraRed Telescoping Rod for Assessment of Chest Compression is denoted by IR-TRACC. Lastly, vertebral locations denoted by 'C,' 'T,' and 'L' are for cervical, thoracic, and lumbar spine followed by the vertebral level represented in the ATD (for example: T8 for the eighth vertebral body in the thoracic spine).

Figure A1. The Hybrid II 50M (HII-50M) ATD reproduced with permission from Humanetics Group (2023i).

Table A1. HII-50M Instrumentation adapted from Mertz & Irwin (2015)

Body Region	Instrumentation
Head	Acceleration (A_x, A_y, A_z)
Neck	
Shoulder	Clavicle Force (F_x, F_z)
Thorax	Displacement D_x (Humanetics Design) Acceleration (A_x, A_y, A_z) Lumbar Spine Force / Moment (F_x, F_y, F_z), (M_x, M_y, M_z)
Abdomen	
Pelvis	Acceleration (A_x, A_y, A_z) (6X) Force (F_x), pelvic submarine indicator bolts (requires modified pelvis)
Upper Extremities	
Lower Extremities	

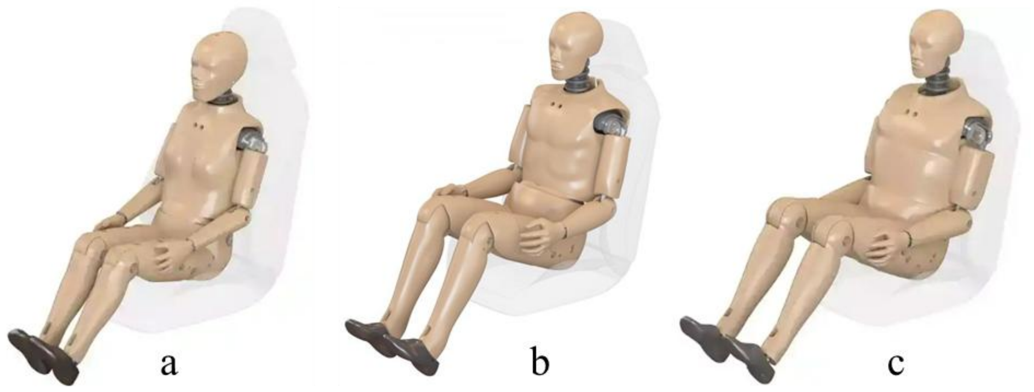

Figure A2. The Hybrid III (HIII) ATD (a) 5th percentile female (5F), (b) HIII 50th percentile male (50M), (c) HIII 95th percentile male (95M). ATDs reproduced with permission from Humanetics Group (2023j, 2023k, 2023l).

Table A2. HIII Instrumentation Adapted from Mertz & Irwin (2015)

Body Region	**Instrumentation**	**5F**	**50M**	**95M**
Head	Acceleration (A_x, A_y, A_z)	Yes	Yes	Yes
Neck	Head/C1 Force / Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)	Yes	Yes	Yes
	C7/T1 Force / Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)	Yes	Yes	Yes
Shoulder	Clavicle Force (F_x, F_z)	Yes	Yes	No
Thorax	Spine Acceleration (A_x, A_y, A_z)	Yes	Yes	Yes
	Spine Force ($F_x, F_y, F_z, M_x, M_y, M_z$)	Yes	Yes	Yes
	Sternum Deflection (δ_x)	Yes	Yes	Yes
	Sternum Acceleration (A_x)	Yes	Yes	No
Abdomen	Lumbar Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)	Yes	Yes	Yes
Pelvis	Acceleration (A_x, A_y, A_z)	Yes	Yes	Yes
	ASIS Force (F_x)	F_x, M_y	Load Bolt	Yes
Upper Extremities				
Lower Extremities	Femur Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)	Yes	Yes	Yes
	Tibia-Femur Displacement (δ_x)	Yes	Yes	Yes
	Knee Clevis Force (F_z)	Yes	Yes	Yes
	Tibia Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)	Yes	Yes	Yes

Figure A3. The THOR-50M ATD reproduced with permission from Humanetics Group (2023b).

Table A3. THOR-50M Dummy Instrumentation Adapted from Humanetics (2023b)

Body Region	**Instrumentation**
Head	Acceleration (A_x, A_y, A_z) Tilt Sensor (Θ_x, Θ_y) Face Force (5X) (F_x) Skull Spring Force (F_z)
Neck	Upper Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Lower Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$
Shoulder	Clavicle Force (4X) F_x & (4X) F_z (total)
Thorax	IR-TRACC Upper Left/Right (D_x, D_y, D_z) IR-TRACC Lower Left/Right (D_x, D_y, D_z) Upper Thoracic Acceleration (A_x, A_y, A_z) Lower Thoracic Acceleration (A_x, A_y, A_z)
Abdomen	IR-TRACC Left/Right (D_x, D_y, D_z)
Pelvis	Acceleration (A_x, A_y, A_z) ASIS Left/Right Force/Moment (F_x, M_y)
Upper Extremities	Upper Arm Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$
Lower Extremities	Acetabulum Force (F_x, F_y, F_z) Femur Force $(F_x, F_z,)$ Leg Lower Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Upper Tibia Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Lower Tibia Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Tibia (Knee) Displacement (D_x) Ankle Angular Displacement $(\Theta_x, \Theta_y, \Theta_z)$ Foot Acceleration (A_x, A_y, A_z)

Figure A4. The Test Device for Human Occupant Restraint (THOR) 5F ATD reproduced with permission from Humanetics Group (2023a).

Table A4. THOR-5F Instrumentation adapted from Humanetics Group (2023a)

Body Region	Instrumentation
Head	Acceleration (A_x, A_y, A_z) Angular Rate Sensor (ARS) ($\omega_x, \omega_y, \omega_z$) Tilt Sensor ($\Theta_x, \Theta_y$) Face (5X) ($F_x$)
Neck	Upper Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Lower Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Lower Neck Acceleration (A_x, A_y, A_z) Tilt Sensor (Θ_y)
Shoulder	Clavicle Force (2X) (F_x, F_z)
Thorax	IR-TRACC Upper Left/Right (D_x, D_y, D_z) IR-TRACC Lower Left/Right (D_x, D_y, D_z) Thorax/Sternum (A_x) Tilt Sensor (Θ_x, Θ_y) Thoracic Spine Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Upper Lumbar Tilt Sensor (Θ_x, Θ_y)
Abdomen	Abdominal Pressure Twin Sensors (2X)
Pelvis	Acceleration (A_x, A_y, A_z) Tilt Sensor (Θ_x, Θ_y) Anterior Superior Iliac Spine Left/Right (F_x, M_y)
Upper Extremities	Upper Arm Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Lower Arm TBD
Lower Extremities	Acetabulum Force (F_x, F_y, F_z) Femur Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Upper Tibia Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Lower Tibia Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Tibia Displacement ($D_x$) Tibia Acceleration ($A_x, A_y$) Achilles Force ($F_z$) Foot Acceleration ($A_x, A_y, A_z$) Foot ARS 3X Rate ($\omega_x, \omega_y, \omega_z$) Foot Tilt Sensor ($\Theta_x, \Theta_y$)

Figure A5. The SID-HIII ATD reproduced with permission from Dan Rhule (Department of Transportation).

Table A5. Instrumentation Table for SID-HIII (Mertz & Irwin, 2015)

Body Region	**Instrumentation**
Head	Acceleration (A_x, A_y, A_z)
Neck	Upper Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)
Thorax	Spine acceleration (A_x, A_y, A_z)
	Rib acceleration (A_y)
	Lumbar ($F_x, F_y, F_z, M_x, M_y, M_z$)
Abdomen	▨
Pelvis	Acceleration (A_x, A_y, A_z)
Upper Extremities	▨
Lower Extremities	Femur ($F_x, F_y, F_z, M_x, M_y, M_z$)

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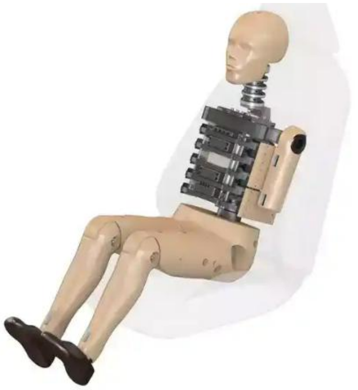

Figure A6. The SID-II Small (SID-IIs) female ATD reproduced with permission from Humanetics Group (2023f).

Table A6. SID-IIs Instrumentation Adapted from Humanetics Group (2023f)

Body Region	**Instrumentation**
Head	Acceleration (A_x, A_y, A_z)
Neck	Upper Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Lower Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$
Shoulder	Shoulder Acceleration (A_x, A_y, A_z) Shoulder Force (F_x, F_y, F_z) Shoulder Displacement (D_y)
Thorax	Thoracic Spine Acceleration at T1 (A_x, A_y, A_z) Thoracic Spine Opposite Ribs (3X) (A_x, A_y, A_z) Thoracic Spine Acceleration Opposite Abdominal Ribs (2X) (A_x, A_y, A_z) Thoracic Rib (3X 2X) (A_x, A_y, A_z) (18 channels) Abdomen Rib (2X 2X) (A_x, A_y, A_z) (12 channels) Thorax Rib to Spine (3X) (F_x) Abdomen Rib to Spine (F_x) Thorax Rib Displacement (3X) (D_y) Abdomen Rib Displacement (3X) (D_y) Lumbar Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$
Abdomen	▨
Pelvis	Acceleration (A_x, A_y, A_z) Pubic (F_y) Ilium (F_y)
Upper Extremities*	Acceleration at Shoulder (A_x, A_y, A_z) Acceleration at Elbow (A_x, A_y, A_z) Elbow Moment (M_x, M_y, M_z)
Lower Extremities	Acetabulum Force (F_y) Femur Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Knee Clevis Force (2X) (F_z) Upper Tibia Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Lower Tibia Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$

*Multi-channel arm replaces standard arm with load cells, accelerometers, and rotation sensors.

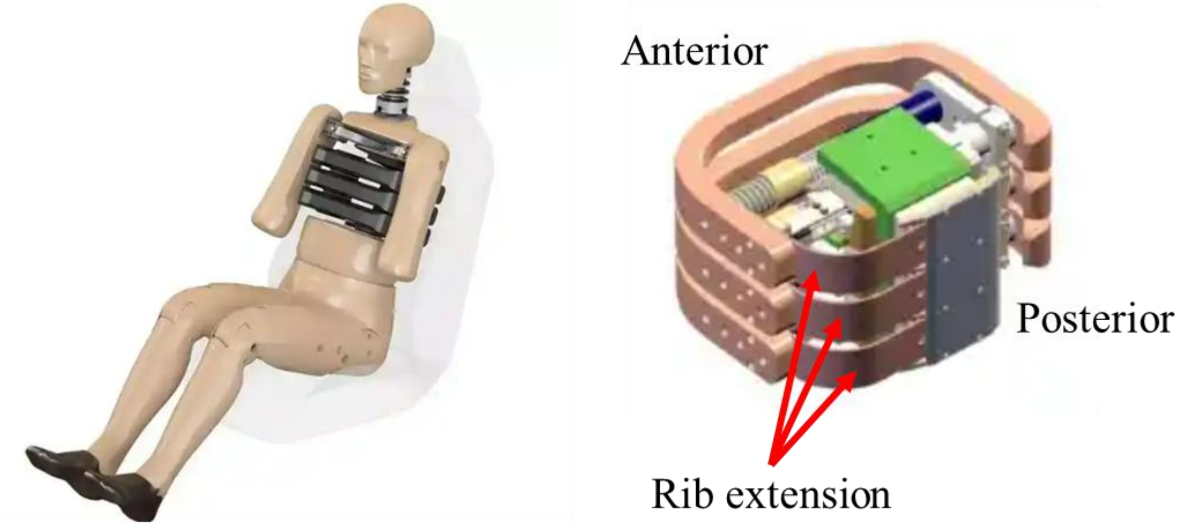

Figure A7. The EUROSID-2 (ES-2) and ES-2re male ATDs with permission from Humanetics Group (2023n). The ES-2re has rib extensions to prevent the seatback foam from getting lodged into a gap that exists in the ES-2

Table A7. ES-2/2re Instrumentation Adapted from Humanetics Group (2023n)

Body Region	**Instrumentation**
Head	Acceleration (A_x, A_y, A_z)
Neck	Upper Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Lower Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)
Shoulder	Acceleration (A_x, A_y, A_z) Shoulder Force (F_x, F_y, F_z)
Thorax	Thoracic Spine Acceleration at T1 (A_x, A_y, A_z) Lumbar Spine Acceleration (A_x, A_y, A_z) Spine Box Rib Force (3X) (F_y) Piston (Rib Slide) Force (3X) (F_x, F_y, F_z) Rib Damper (Rib Slide) Force (3X) (F_x, F_y, F_z) Thoracic Spine Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Thorax Rib Displacement (3X) (D_y) Lumbar Spine Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Back Plate Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)
Abdomen	Abdominal (F_y)
Pelvis	Acceleration (A_x, A_y, A_z) Pubic Force (F_y)
Upper Extremities	
Lower Extremities	Femur Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)

Figure A8. WorldSID-50M reproduced with permission from Humanetics Group (2023d)

Table A8. WorldSID-50M Instrumentation Adapted from Humanetics Group (2023d)

Body Region	**Instrumentation**
Head	Acceleration (A_x, A_y, A_z)
Neck	Upper Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Lower Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)
Shoulder	Shoulder Force (F_x, F_y, F_z)
Thorax	Upper Acceleration (A_x, A_y, A_z) Lower Acceleration (A_x, A_y, A_z) Each Rib Acceleration (6X) (A_y) Rotational Acceleration (α_x) Tilt Sensor (Θ_x, Θ_y) Lumbar Spine Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Sacroiliac Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)
Abdomen	
Pelvis	Acceleration (A_x, A_y, A_z) Rotational Acceleration (α_x) Tilt Sensor (Θ_x, Θ_y)
Upper Extremities	Elbow Moment (M_x, M_y)
Lower Extremities	Mid-Femur Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Femoral Neck Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Knee Contact Force (2X) (F_y) Knee Angular Displacement (Θ_y) Upper Tibia Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Lower Tibia Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)

Figure A9. The WorldSID-5F reproduced with permission from Humanetics Group (2023c).

Table A9. WorldSID-5F Instrumentation (Humanetics, 2023c)

Body Region	Instrumentation
Head	Acceleration (A_x, A_y, A_z) Rotational Acceleration ($\alpha_x, \alpha_y, \alpha_z$) Tilt Sensor ($\Theta_x, \Theta_y$)
Neck	Upper Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Lower Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)
Shoulder	Shoulder Force (F_x, F_y, F_z)
Thorax	Upper Acceleration (A_x, A_y, A_z) Lower Acceleration (A_x, A_y, A_z) Each Rib (6x) (A_y) Lumbar Spine Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Sacroiliac Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Tilt Sensor ($\Theta_x, \Theta_y$) Rotational Acceleration ($\alpha_x, \alpha_y, \alpha_z$) IR-TRACC Left/Right (5X) (D_x, D_y) String Potentiometer on Top Rib (D_x)
Abdomen	
Pelvis	Acceleration (A_x, A_y, A_z) Pubic Force (F_y) Tilt Sensor (Θ_x, Θ_y) Rotational Acceleration ($\alpha_x, \alpha_y, \alpha_z$)
Upper Extremities	
Lower Extremities	Femur Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Femoral Neck Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Knee Contact Force (2X) (F_y) Knee Angular Displacement (Θ_y) Upper Tibia Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Lower Tibia Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)

Figure A10. The Military SID (MIL-SID) ATD reproduced with permission from Humanetics Group (2023e).

Table A10. MIL-SID Instrumentation (Humanetics Group, 2023e)

Body Region	**Instrumentation**
Head	Acceleration (A_x, A_y, A_z)
Neck	Upper Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Lower Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)
Shoulder	Shoulder Force (F_x, F_y, F_z)
Thorax	Upper Acceleration (A_x, A_y, A_z) Lower Acceleration (A_x, A_y, A_z) Rib Displacement (3X) (D_x, D_y, D_z) Back Plate Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Spine Box (Rib Force) (F_x, F_y, F_z) Rib Piston Force (F_x, F_y, F_z) Rib Damper Force (F_x, F_y, F_z) Lumbar Spine Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)
Abdomen	Force (F_x, F_y, F_z)
Pelvis	Pubic Force (F_y)
Upper Extremities	
Lower Extremities	Femur Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Upper Tibia Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Lower Tibia Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$)

Figure A11. The Biofidelic Rear Impact Dummy II (BIORID-II) reproduced from Humanetics Group (2023o).

Table A11. BIORID-II Instrumentation (Humanetics Group, 2023o)

Body Region	**Instrumentation**
Head	Acceleration (A_x, A_y, A_z) Skull Cap Force (F_x, F_y, F_z)
Neck	Upper Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) C4 Acceleration ($A_x, A_z$)
Shoulder	
Thorax	T1 Force/Moment (F_x, F_z, M_y) or (F_x, F_y, M_y) T1 Acceleration (A_x, A_z) T8 Acceleration (A_x, A_z) L1 Acceleration (A_x, A_z) L5 Spine Force/Moment ($F_x, F_y, F_z, M_x, M_y, M_z$) Spring Tube Anterior Force (F_z) (muscle substitute) Spring Tube Posterior Force (F_z) (muscle substitute)
Abdomen	
Pelvis	Acceleration (A_x, A_y, A_z)
Upper Extremities	
Lower Extremities	

Figure A12. ADAM reproduced from Thomas (2014) with permission of Christopher Perry, Biodynamics Section, Wright Patterson Air Force Base. Instrumentation includes linear and angular accelerometers, neck/lumbar load cells, and angular potentiometers. These are no longer available for procurement.

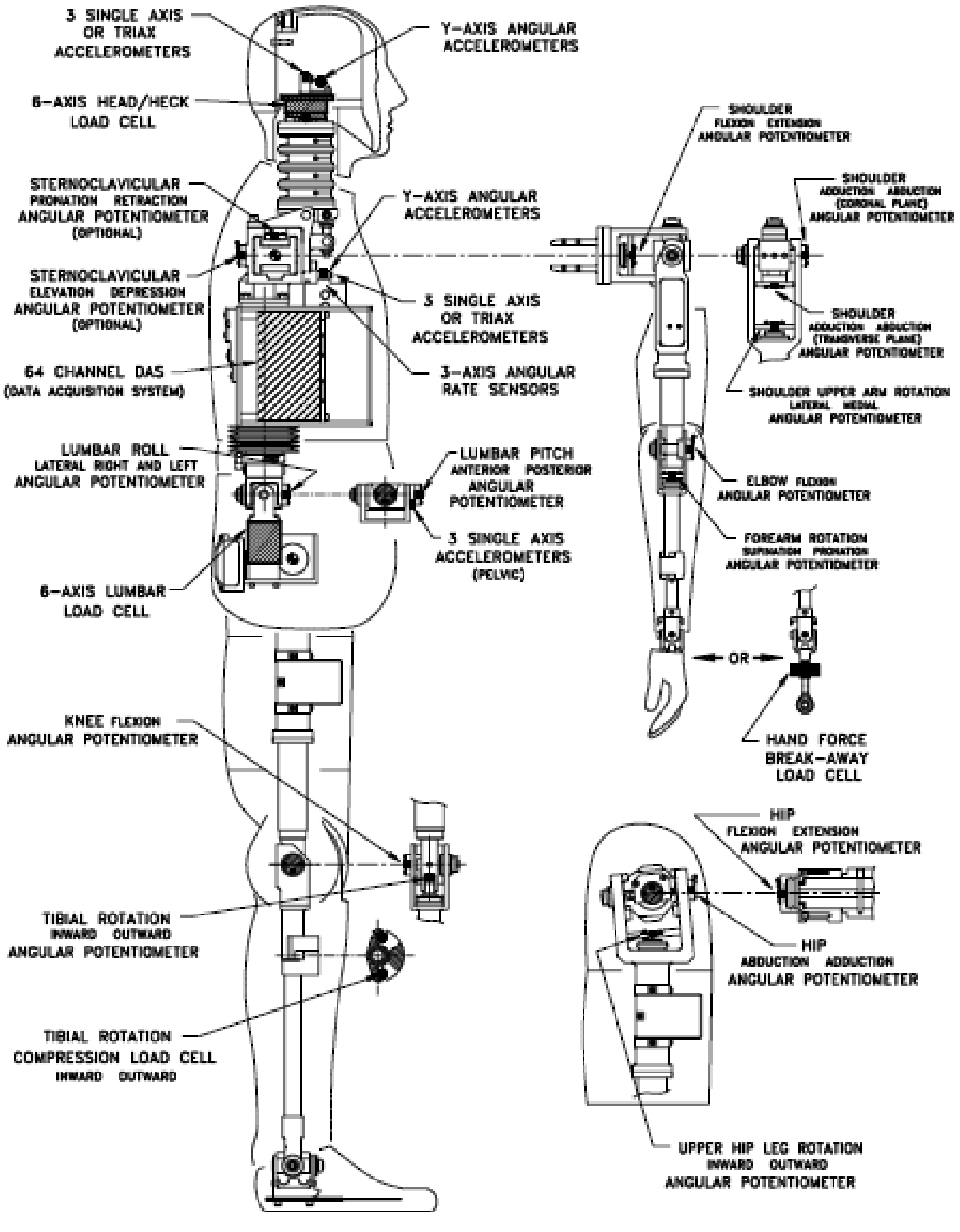

Figure A13. ADAM instrumentation reproduced from Thomas (2014) with permission of Christopher Perry, Biodynamics Section, Wright Patterson Air Force Base. Instrumentation included a 6-axis head/neck load cell, a 6-axis lumbar load cell, and a triaxial accelerometer package in the lower lumbar area, the chest, and head. It also had angular potentiometers for 31 joint measurements. Lower leg rotations had single axis load cells for their measurements.

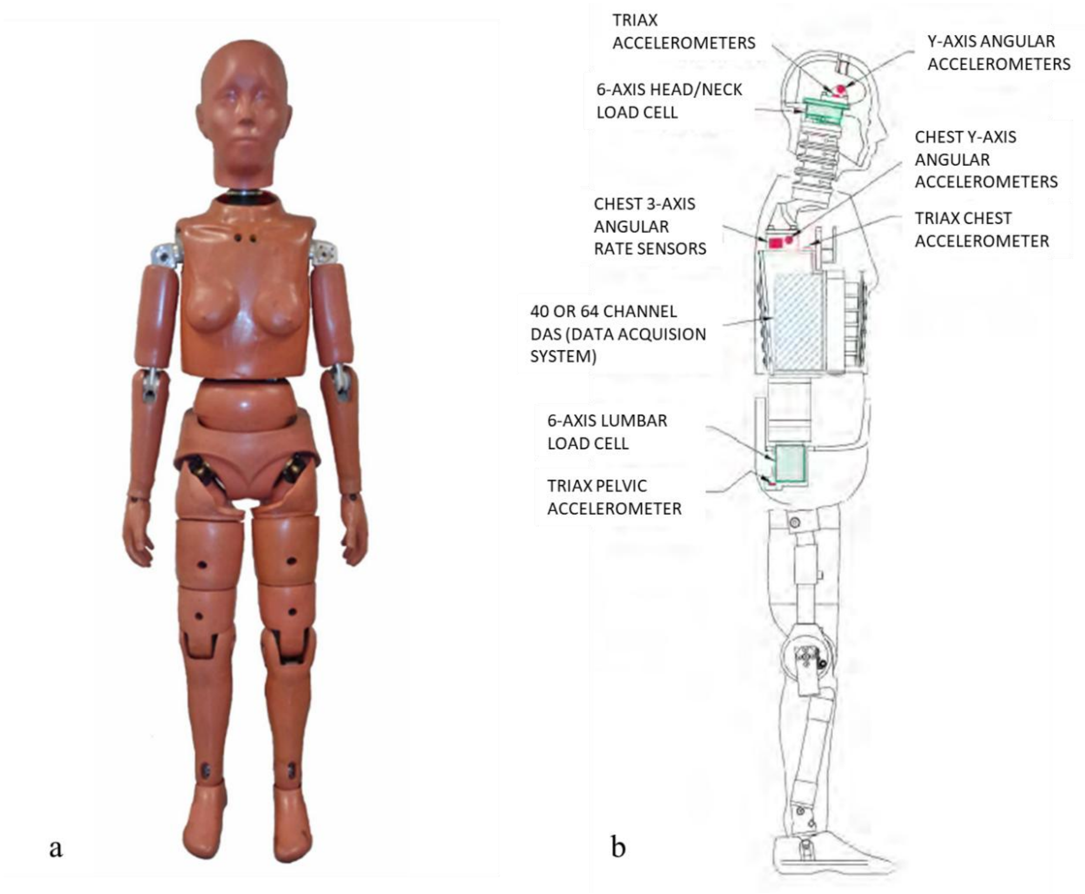

Figure A14. (a) The LOIS Manikin and (b) instrumentation reproduced from Thomas (2014) used with permission from Christopher Perry, Biodynamics Section, Wright Patterson Air Force Base. Instrumentation includes linear and angular accelerometers, angular rate sensors, and neck/lumbar load cells.

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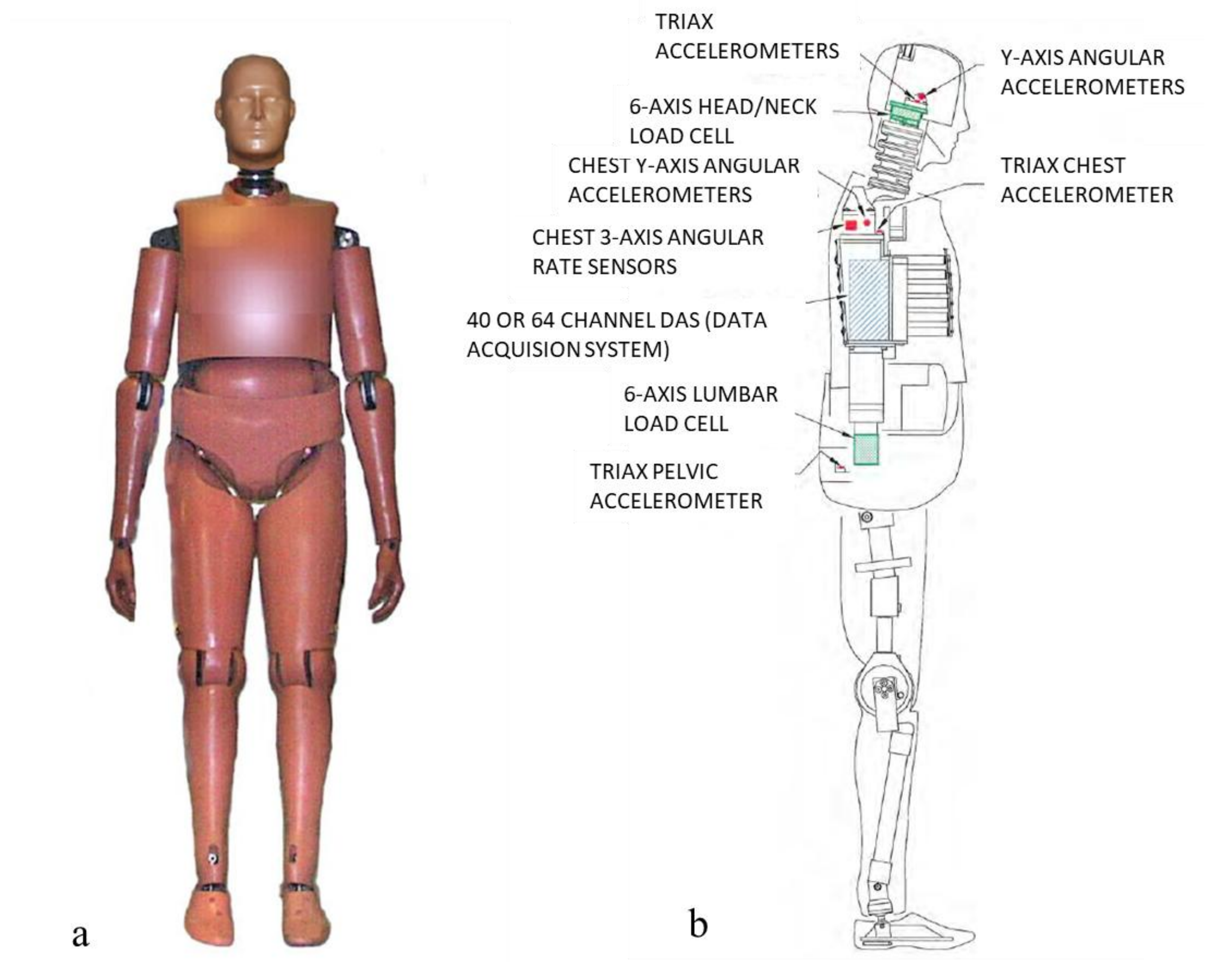

Figure A15. LARD reproduced from Thomas (2014) used with permission from Christopher Perry, Biodynamics Section, Wright Patterson Air Force Base. Instrumentation includes linear and angular accelerometers, angular rate sensors, and neck/lumbar load cells.

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Figure A16. WIAMan Technology Demonstrator seated in the vertical loading condition reproduced with permission from David Weyland (U.S. Army DEVCOM Ground Vehicle Systems Center).

Table A12. Instrumentation Table for the WIAMan Manikin Adapted From Pietsch et al. (2016)

Body Region	**Instrumentation**
Head	Acceleration (A_x, A_y, A_z) Angular Rate $(\omega_x, \omega_y, \omega_z)$
Neck	Upper Neck C1 Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Lower Neck/C7 Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z, A_x, A_y, A_z)$ Lower Neck/C7 Angular Rate $(\omega_x, \omega_y, \omega_z)$
Shoulder	Force (F_x, F_y, F_z) Deflection (D_y)
Thorax	Sternum Acceleration (A_z) Sternum Angular Rate $(\omega_x, \omega_y, \omega_z)$ T5 Force/Moment $(F_x, F_y, F_z , M_x, M_y, M_z)$ T12 Force/Moment $(F_x, F_y, F_z , M_x, M_y, M_z)$ T12 Acceleration (A_x, A_y, A_z) T12 Angular Rate $(\omega_x, \omega_y, \omega_z)$ L5 Force/Moment $(F_x, F_y, F_z , M_x, M_y, M_z)$
Abdomen	
Pelvis	Acceleration (A_x, A_y, A_z) Angular Rate $(\omega_x, \omega_y, \omega_z)$
Upper Extremities	
Lower Extremities	Femoral Neck Force (F_x, F_y, F_z) Femur Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Femur Acceleration (A_x, A_y, A_z) Femur Angular Rate $(\omega_x, \omega_y, \omega_z)$ Tibia Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Tibia Acceleration (A_x, A_y, A_z) Tibia Angular Rate $(\omega_x, \omega_y, \omega_z)$ Calcaneus Force (F_x, F_y, F_z) Foot/Metatarsals Acceleration (A_x, A_y, A_z) Foot/Metatarsals Angular Rate $(\omega_x, \omega_y, \omega_z)$

Figure A17. The FAA HIII-50M ATD reproduced with permission from Humanetics Group (2023m).

Table A13. FAA HIII-50M Instrumentation (Humanetics Group, 2023m)

Body Region	**Instrumentation**
Head	Acceleration (A_x, A_y, A_z)
Neck	Upper Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Lower Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$
Shoulder	
Thorax	Acceleration (A_x, A_y, A_z) Deflection (D_x) Thoracic Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Lumbar Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$
Abdomen	
Pelvis	Acceleration (A_x, A_y, A_z)
Upper Extremities	
Lower Extremities	Femur Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Knee Displacement (D_x) Knee Clevis Force (F_z) Upper Tibia Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Lower Tibia Force/Moment $(F_x, F_y, F_z, M_x, M_y, M_z)$ Anterior Tibia Force (F_z) Ankle Force/Moment $(F_x, F_y, F_z, M_x, M_y)$

Figure A18. The PRIMUS ATD reproduced with permission from Peter Schimmelpfennig, CTS.

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Appendix B. Recommended IARVs for the Military Environment

Table B1. IARVs by Body Region and ATD (Rhodes et al., 2022a)

Parameter	Body Region	ATDs											
		HIII			FAA HIII 50th Male	THOR	SIDs						FOCUS
		5th Female	50th Male	95th Male			ES-2/2re	SID-IIs	SID-II	EUROSID	BIOSID	SID-HIII	
		Validated IARVs for ATDs											
HIC (15 milliseconds [ms])	Head	HIC ≤779	HIC ≤700	HIC ≤670	HIC ≤700			HIC ≤779			HIC ≤700		
HIC (36 ms)	Head	HIC ≤1000	HIC ≤1000		HIC ≤1000					HIC ≤1000		HIC ≤1000	
Peak Head Acceleration (G)	Head	150	150	150									
Craniomaxillo-Facial Injury Criteria (Newtons [N])	Frontal Bone (AP)												2523
	Frontal Bone (Lateral)												2382
	Nasal Bone (AP)												616
	Nasal Bone (Lateral)												115
	Maxilla (AP)												1226
	Zygoma												834
	Mandible												TBD

Table B1.*Table B1*.. IARVs by Body Region and ATD (Rhodes et al., 2022a) (Continued)

Parameter	**Body Region**	**ATDs**											
		HIII			**FAA HIII 50th Male**	**THOR**	**SIDs**						**FOCUS**
		5th Female	**50th Male**	**95th Male**			**ES-2/2re**	**SID-IIs**	**SID-II**	**EUROSID**	**BIOSID**	**SID-HIII**	
		IARVs for Validated ATDs											
Neck Peak Force and Moments	Neck	See Reference Criteria Section in Rhodes et al. (2022a), Table C21							See Reference Criteria Section in Rhodes et al. (2022a), Table C21				
Nij	Neck	≤1.0[*]											
Beam Criterion	Neck	≤1.0[**]				≤1.0[**]							
Thoracic Spine Acceleration Criteria (3 ms) (G)	Chest	≤60	≤60	≤55	≤60			≤73			≤60		
Chest Compression (Shoulder Belt) (millimeters [mm])	Chest	41	50	55									
TTI (G)	Chest									TTI (PMHS & ATD) ≤85 (four side doors); TTI (PMHS & ATD) ≤90 (two side doors)			
Lumbar Injury Criteria (pounds [lb])	Lumbar Spine		1135		1223								
Pelvic Acceleration Criteria (N)	Pelvis						3250			3250			

[*] Using ATD specific critical intercepts (Rhodes et al. [2022a]; See Table 5).
[**] Using critical intercepts (Rhodes et al. [2022a]; See Table 6).

Table B2. IARVs by Body Region and ATD (Rhodes et al., 2022b)

Parameter	Body Region	HIII IARV		
		5F	50M	95M
Elbow Hyperextension Criteria (Newton-meters [Nm])	Upper Extremity	56[*]		
Femur Axial Compression (N)	Lower Extremity	6,800	10,000	12,700

[*] SAE HIII instrumented arm.

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