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Development and Verification of Body Armor Target Geometry Created Using Computed Tomography Scans

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14. ABSTRACT

This report documents a novel technique for creating target geometry, which includes computed tomography (CT) scanning, segmentation, and retopology of the Improved Outer Tactical Vest and Soldier Protection System (SPS) armor systems. SPS target geometry was created for use in MUVES/ Operational Requirement-based Casualty Assessment (ORCA) preshot prediction modeling analysis. Previous methods of target geometry modeling consisted of manual measurement of armor systems and translating those measurements to computer-aided design geometry, which can be tedious and error prone. Here we demonstrate proof of concept by dressing a foam representation of the ORCA man with the armor systems. The manikin was scanned using a medical CT scanner. The scans were then loaded into Materialise's Mimics software, segmented, and exported as 3-D geometry. This geometry was then loaded into Pixologic's ZBrush software for geometry cleanup and retopology. The retopologized model was then loaded into Rhino3D software to create target surface geometry for MUVES/ORCA. The completed SPS large ORCA measurements were all within 5% of the physical measurements, verifying that the process used to create the geometry resulted in the appropriate sizes on the ORCA model.

15. SUBJECT TERMS

body armor, computed tomography, segmentation, CAD geometry, target modeling, 3-D modeling, scanning, SPS, IOTV

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Executive Summary

Here we document proof of concept for an efficient method of modeling target geometry. This method captures placement and size of the armor system to the computer-aided design (CAD) human geometry model (referred to throughout as ORCA man) that is used in the Operational Requirement-based Casualty Assessment (ORCA) personnel vulnerability model. In this report, we reference a foam manikin manufactured from ORCA CAD geometry[1]. The foam manikin was created as a life-size representation of the ORCA man. We also explain how the manikin was dressed and scanned. We then go into detail as to what tools were used for the process of segmentation, retopology, and final creation of each piece of personal protective equipment (PPE) within the entire system. At the end, a full render of the ORCA CAD model with the resulting PPE target geometry is displayed. The purpose of this report is to give insight on how the results of computed tomography scanning can lead to more accurate representations of PPE target geometry in size, shape, and placement.

[1] Gillich P, Roach L. Methodology for assessing tri-service personnel casualties. Arlington (VA): Aircraft Survivability; Joint Aircraft Survivability Program Office; 2009 Spring.

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1. Introduction

This report documents a new process developed to support the rapid development of computer-aided design (CAD) geometry to model personal protective equipment (PPE). The armor detailed in this report was developed and used in modeling and simulation for analysis of the Tier 4 Soldier Protection System (SPS) compared to the Improved Outer Tactical Vest (IOTV). We provide evidence for the verification that was conducted to ensure that the geometry is accurate for its intended purpose.[1,2] The goal of modeling the PPE CAD geometry was to create a representation of the armor system to scale relative to the Operational Requirement-based Casualty Assessment (ORCA) man model and place the armor system in the correct location relative to anatomical landmarks.

Previously, to create the PPE CAD models, the engineer manually measured and then reconstructed new individual components of the PPE in CAD software. The manually collected measurements were used to wrap ORCA man with each PPE component. User-fitting instructions from each system's technical manuals were used to guide size and placement of the PPE on the personnel CAD. Although this method resulted in dimensionally accurate individual PPE components, it could result in unnatural spatial relationships among PPE components or among the PPE components and other components in the system or ORCA man. This method was also time-consuming because iterative CAD development was often necessary to mitigate these issues. To improve this methodology and create a more precise and efficient model, we developed a novel approach involving computed tomography (CT) scanning of the PPE systems already fit to a human body model that was the same size and shape as the computerized model. The methodology and results from development of this new system are introduced in this report.

2. Methods, Assumptions, and Procedures

To reduce production time and increase accuracy of armor placement for vulnerability/lethality modeling, the US Army Research Laboratory's Survivability/Lethality Analysis Directorate explored a new process for CAD model creation. This methodology included CT scanning using the General Electric BrightSpeed model and placing the physical armor system on a foam manikin representative of ORCA man. This foam ORCA-man surrogate (referred to throughout as foam manikin) is optimal for scanning given it is lightweight and has low density. It also provides real-life dimensions and fit of the armor system to the ORCA-man geometry, which is used for vulnerability/lethality modeling.

Four systems were CT-scanned on the foam manikin: a medium IOTV, the large IOTV pelvic under garment/pelvic outer garment (PUG/POG) system, a medium SPS, and a large SPS. Two scans for each system were conducted. The first included all pieces of the system: the cloth vest holding the hard plates and ballistic soft armor, the PUG/POG; the second included only the ballistic soft armor (outside of its cloth lining) placed on the foam manikin. This latter scan was to prevent scan artifact and material bunching or separation of soft armor layers. Only the large PPE systems were segmented, as those were being created to support SPS live-fire evaluations. Figure 1 displays the full IOTV and SPS systems on the ORCA foam model.

Fig. 1 Full IOTV (left) and SPS (right) systems on the foam ORCA manikin

The CT scans resulted in Digital Imaging and Communications in Medicine (DICOM) formatted data. DICOM format is the international standard for medical imaging.[3] The DICOM data and header files provide a series of stacked images along with metadata and measurements. For this process, we used the DICOM files to understand and create a 3-D model of each armor system by examining and defining layers of materials. After the scans were collected, they were analyzed, segmented, retopologized, and finalized as CAD geometry.

To segment the CT scans, each respective set of the DICOM images were loaded into Materialise's Mimics analysis software.[4] Here, each PPE component was segmented into individual pieces, which together define the entire armor system. Segmentation is the process of applying a 2-D mask to each image in the DICOM image series to define the armor system object of interest. The defined 2-D mask was then used to generate 3-D geometry, as shown in Fig. 2. The 2-D masks were created using a series of density selection tools as well as manual selection tools. The masks often have high resolution and artifact interference that result in initial geometry that requires further refinement to ensure the model is smooth and watertight.

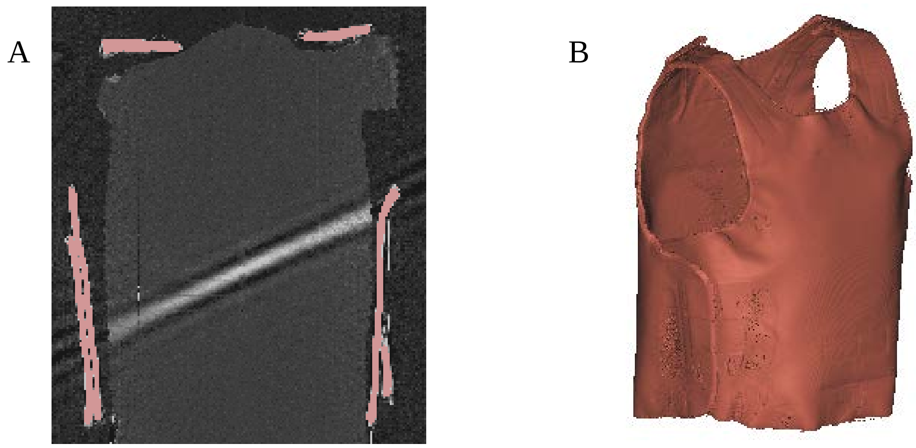

Fig. 2 IOTV soft armor in Mimics software showing a) soft armor (red mask) placed on ORCA foam model in coronal slice and b) rough soft armor geometry created from segmentation

Given that the 2-D masks were created using DICOM files, which preserved units of measurement, this segmentation process preserved the armor's shape, size, and scale. After creation of the 3-D geometry, each piece of armor was exported as an STL file, Mimics software's only 3-D format. The STL files were converted from STL files to OBJ, the format required for import into Pixologic's ZBrush, a 3-D modeling and sculpting program developed to work with organic and high-resolution polygonal models.[5] ZBrush provides advance tools to clean up and redefine the topology of geometry, referred to as retopology. Here, each piece of geometry defining a different portion of the armor system was retopologized, as shown in Fig. 3. The process of retopology ensured the shape and size of the geometry while removing noise and artifacts from the segmentation process. This retopology process resulted in a plane that defined shape and size of the armor.

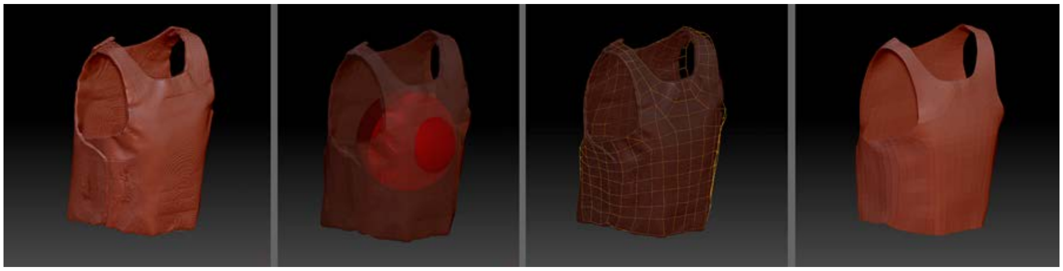

Fig. 3 Retopology process from left to right: a) the segmented model exported from Mimics and imported into ZBrush; b) the imported mesh defined as a template; c) new geometry created in the space of the template; and d) the template converted to a polygonal plane

Each OBJ model was imported and exported from ZBrush as an individual portion of the armor system. The importing/exporting of models, as well as model conversion can lead to improper orientation or scaling. Furthermore, the different CT scans were collected with different degree field of view (DFOV) settings. Collecting the scans with the finest resolution of DFOV increased resolution of the segmentation process; however, it places each piece of geometry at a different origin in space. To account for this, landmark points relative to the ORCA geometry were exported from Mimics and imported into Autodesk Maya with the segmented armor systems,[6] as shown in Fig. 4.

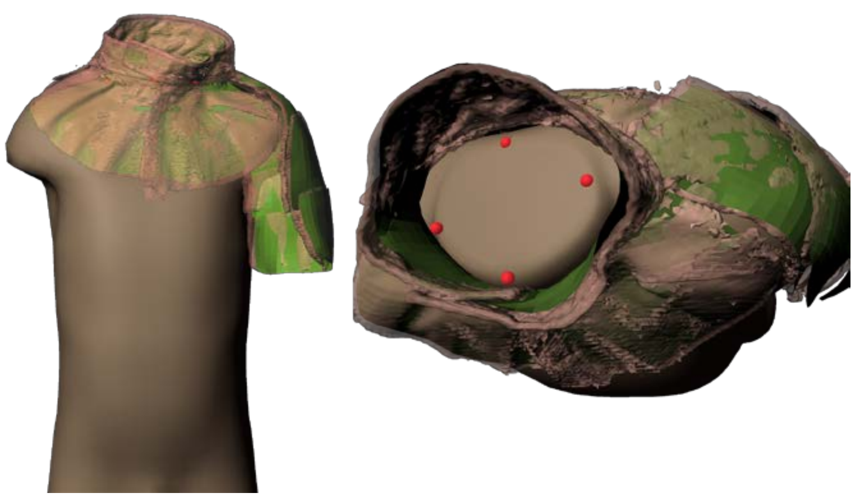

Fig. 4 To ensure proper fit and placement of the final geometry, the retopologized geometry (green) was aligned with the models segmented from CT data (peach). From each Mimics file, landmarks were exported to align scale and placement of the segmented geometry with the ORCA geometry. This ensured placement of the different parts of the system relative to each other.

Autodesk Maya was used to piece the armor systems back together at the proper scale and orientation, ensuring placement and morphology relative to the ORCA model geometry. Autodesk Maya is a 3-D modeling and animation program well suited to handle groups of large-scale 3-D objects. The new retopologized models were imported into Maya. After all pieces of the armor system were scaled and oriented to the ORCA-man geometry, they were exported as OBJ models, importable by Rhino3D.

The final stage in the modeling creation process involved placing each piece of protection on ORCA-man in the appropriate configuration and thickness. To get each piece fit onto the model, some manual adjustments had to be made. This process was completed using Rhino3D software (McNeel North America).[7]

There were 2 methods for completing the geometry and fit of each model. The first method involved constructing the components from direct measurements of the item that were then dressed onto the foam manikin to achieve accurate dimensionality and realistic protection coverage. In this case, the CT data were used as a guide for placement and shape. The ballistic combat shirt, vest, cummerbund, and ballistic pelvic protection were modeled using this methodology, and an example of the process is shown in Fig. 5.

Fig. 5 The CT data for the SPS vest (gray, left) were used a guide to create curves representing the structure of the vest component (wire frame, center), and then the curves were used to develop the final idealized vest geometry (red, right) to be placed on ORCA man

The second method for the creation of protective geometry involved using the CT data directly. These components were compared to scans of the PPE on the foam manikin to ensure proper fit and adjusted as needed. In these components, symmetry was preserved either by mirroring entire components or by splitting the CT data down the middle and mirroring one side to the other. This method was used for the ballistic belt, femoral protection, pelvic protection, and soft armor side protection components. An example of this methodology is shown in Fig. 6, where the right soft armor side protection was created directly from CT, a thickness was applied, and then the entire component was mirrored to the left side to complete both components for the ORCA-man CAD model.

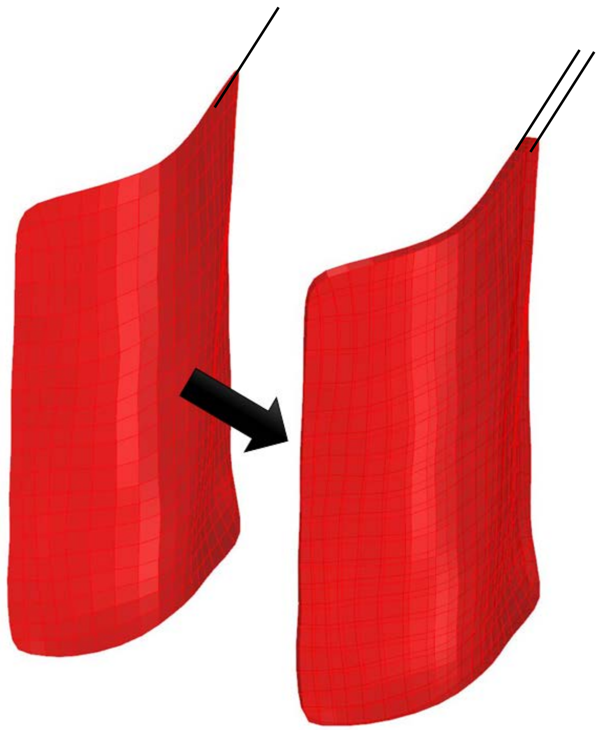

Fig. 6 The surface of the right side soft protection was created from the CT mask. To finalize the geometry mesh, a thickness was applied based on caliper measurements of the soft armor (highlighted by black diagonal lines at top right). This right plate was then mirrored to the left side to create symmetric protection on the ORCA-man CAD model.

For some of the more complicated components, such as the deltoid protection in the SPS shirt, both methods were used. In these cases, the first method was used to achieve appropriate shape and fit on one side, and then the entire component was mirrored to the opposite side to maintain symmetry.

Once the protection was fit onto the ORCA-man CAD model, measurements were taken to verify that the size of the PPE CAD geometry correlated to the physical size of the PPE/body armor. Examples of the measurement methods from CT and the geometry are shown in Fig. 7.

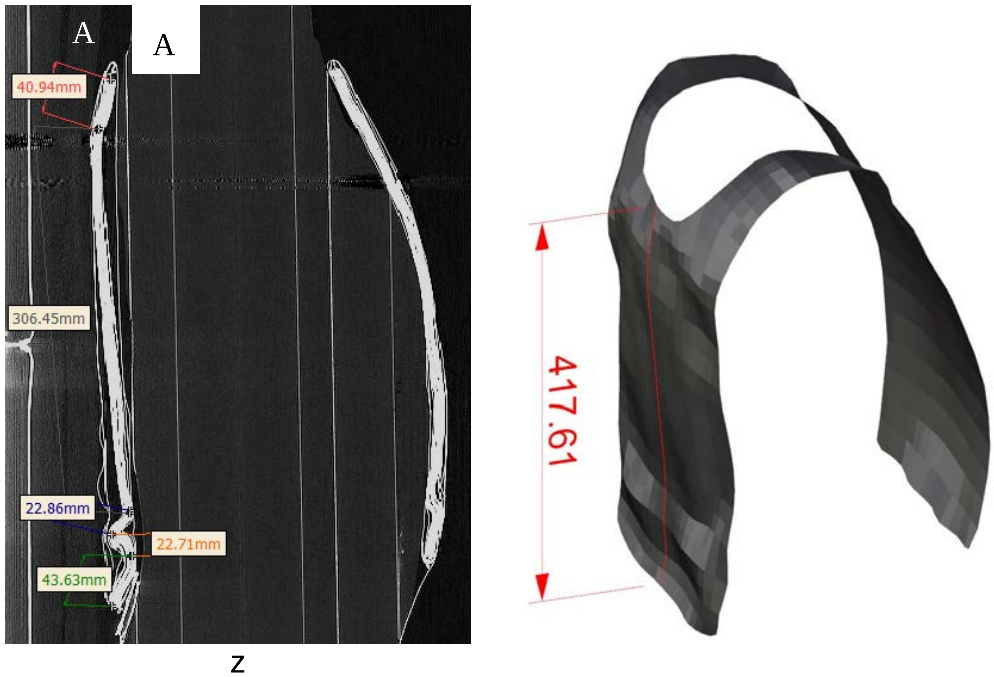

Fig. 7 Example of measurements taken to confirm appropriate size and fit when reconstructing components for modeling. a) Multiple measurements were taken on the soft armor on CT to follow the contours; the final measurement was the summation of these 5 measurements for the SPS large back vest height. b) Once the component was loaded, the corresponding curvilinear measurement was taken in Rhino3D to ensure appropriate size and scale.

3. Results and Discussion

After constructing the full SPS Tier 4 armor system as CAD geometry, we determined this methodology an effective means of ensuring size, shape, and relative placement of each PPE body armor on ORCA-man CAD model. Comparative measurements for each of the systems are shown in Table 1. The IOTV large CT was not used for construction of the vest, as it preexisted; therefore, only the POG measurements are included for that system. The large SPS vest was modeled from CT scans, so the ORCA model measurements are provided for that system. The measurements for the large SPS system were all within 5% of the physical measurements, verifying that the process used to create the geometry resulted in the appropriate sizes on ORCA-man CAD model.

Table 1 Verification of geometry size for protection systems

System	Measured from	Front vest width at midchest (mm)	Back vest height at midline (mm)	Side soft prot. width (mm)	Back POG height at midline (mm)	Front pelvic prot. width (mm)	Front pelvic prot. height at leg (mm)
IOTV medium	Physical	298	460	NA	219	NA	NA
	CT scan	328.97	464.94	NA	217.75	NA	NA
IOTV large	Physical	328	492	NA	189	NA	NA
	CT scan	…	…	…	186.72	NA	NA
SPS medium	Physical	288	410	175	NA	180	89.8
	CT scan	292.33	424.12	175.79	NA	179.65	101.58
SPS large	Physical	310	427	175	NA	240	89.8
	CT scan	305.97	436.59	179.8	NA	234.10	94.52
	ORCA man	303.19	417.61	183.74	NA	239.97	90.16

In addition to verifying sizes of protection, visual inspection was performed to confirm the appropriate fit of protection systems on the ORCA manikin. The SPS medium and large systems are shown on the foam ORCA manikin in Figs. 8 and 9. The first set features the SPS Tier 1 (mounted configuration) system, while the second set (dismounted configuration) features the full SPS system. The IOTV was also fit to the ORCA manikin and photos of the medium and large IOTV are provided in Fig. 10.

Fig. 8 SPS Tier 1 protection system shown on the foam ORCA manikin (without the shirt so that fit of vest could be better assessed). The images provide a visual comparison of fit between the medium and large SPS systems on the foam ORCA manikin.

Fig. 9 SPS Tier 4 protection system shown on the foam ORCA body. The images provide a visual comparison of fit between the medium and large SPS systems on the foam ORCA manikin.

Fig. 10 IOTV protection system shown on the foam ORCA body. The images provide a visual comparison of fit between the medium and large IOTV systems on the foam ORCA manikin.

After completion of the geometry development, the components for each set of protection were placed on the ORCA-man CAD model. Final fit adjustments were made to ensure components overlap and fit properly. Figure 11 shows the completed ORCA model wearing a) the IOTV large system and b) the SPS large system with Tier 4 components. Each piece of protection was originally modeled independently, as identified by the different colors, and was then placed back on ORCA-man CAD model for the final geometry configuration.

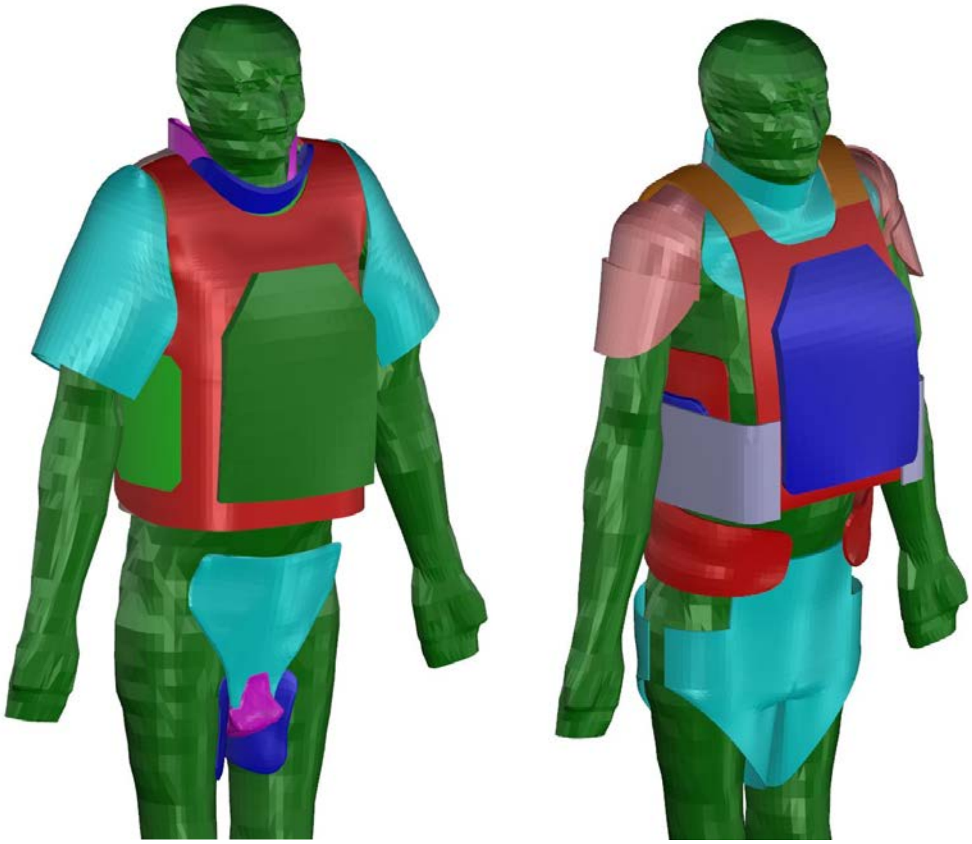

Fig. 11 ORCA model complete with size large systems: a) ORCA man wearing IOTV large components and b) ORCA man wearing SPS large Tier 4 components

Previously, personal protection was modeled by measuring specific points on the system manually to create idealized geometry. This method was time consuming, repeated for every item being modeled, and potentially glossed over small changes in shape or size. This manual method was also difficult when components were built with overlapping protection stitched into the system, such as with the POG and shoulder/deltoid protection in the SPS shirt. The same issues would arise if performing laser scanning using a 3-D scanner to capture external features of the system for modeling. By CT scanning the protection systems on the foam ORCA manikin, not only were the modelers able to see overlapping protection, but also able to build the geometry against the ORCA manikin to achieve proper fit on the ORCA-man CAD model. The use of CT allows for digital 3-D models to be constructed using nondestructive testing and captures both internal and external features of systems. Common applications of CT give credence to its use for body armor model development. These include, but are not limited to, scanning for flaw detection, failure analysis, metrology, assembly analysis, and reverse engineering.

4. Conclusions

CT analysis paired with traditional geometry construction methods allowed for development of CAD geometry of the appropriate size and optimum fit on the ORCA-man CAD model. This model was used to support the live-fire test and evaluation of the SPS. The new methodology for generating the PPE model saved time and resulted in a more precise computer model for evaluating protection.

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List of Symbols, Abbreviations, and Acronyms

2-D	2-dimensional
3-D	3-dimensional
CAD	computer-aided design
CT	computed tomography
DFOV	degree field of view
DICOM	Digital Imaging and Communications in Medicine
IOTV	Improved Outer Tactical Vest
ORCA	Operational Requirement-based Casualty Assessment
PPE	personal protective equipment
PUG/POG	pelvic under garment/pelvic outer garment
SPS	Soldier Protection System

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