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A METHODOLOGICAL FRAMEWORK FOR THE EVALUATION OF FORM, FIT, AND FUNCTION OF BODY ARMOR SYSTEMS

by
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The following report outlines a framework of strategies for planning Human Systems Integration (HSI) evaluations to consistently measure the inter- and intra-effects of BA systems on Warfighter/mission performance. The strategies outlined within this document are based on significant BA system evaluations carried out over many years by subject matter experts (SMEs) from Combat Capabilities Development Command Soldier Center (DEVCOM SC) and partner agencies within the Army, US DoD, and international partners (e.g., The Technical Cooperation Program).

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INTRODUCTION

While ballistic protective body armor (BA) protects Warfighters against a range of threats, it also impedes their mobility and lethality (Scharre and Fish, 2018). These three pillars (protection, mobility and lethality, also known as the "Iron Triangle") are in a constant tug of war as mission requirements, technology, materials, and product designs change. The United States Department of Defense (DoD) continually develops, tests, and modifies BA systems for the Joint Services (Army, Air Force, and Navy/Marines), systematically improving BA systems' form, fit, and function, resulting in more highly effective armed forces (Howard 2020). Materials and technical performance testing (e.g., blast/ballistics, flame resistance, component parts reliability, etc.) are frequently conducted in parallel with product development and engineering (Abtew et al., 2020; David et al., 2009; Xia, 2018). While all these tests are necessary, understanding the Warfighter-BA system interaction is critical to safely completing missions at the desired task performance level (Mitchell 2013; Choi et al., 2016; Choi et al., 2018; Kollock et al., 2018). Understanding how to test and evaluate these systems is essential to ensuring Warfighter needs are met.

Purpose

This document provides a framework of strategies for planning Human Systems Integration (HSI) evaluations to consistently measure the inter- and intra-effects of BA systems on Warfighter/mission performance. The strategies outlined within this document are based on significant BA system evaluations carried out over many years by subject matter experts (SMEs) from Combat Capabilities Development Command Soldier Center (DEVCOM SC) and partner agencies within the Army, US DoD, and international partners (e.g., The Technical Cooperation Program). These strategies were brought together in this one document during the period September 2022 through November 2023.

Scope

This document presents a framework for evaluating the key HSI metrics (i.e., form, fit, and function) of torso-worn BA systems (Figure 1). Torso-worn BA systems are primarily worn over duty uniforms (as opposed to concealable armor worn under uniforms) and are typically a vest style with level IV protection comprised of a carrier, soft armor, and rigid plate(s). This framework builds on past BA systems research. Strategies are flexible and easily adaptable to varied HSI questions regarding a broad range of BA systems, including extremity and concealable armor as well as other ancillary clothing and equipment. Additionally, other strategies may be incorporated to strengthen the framework.

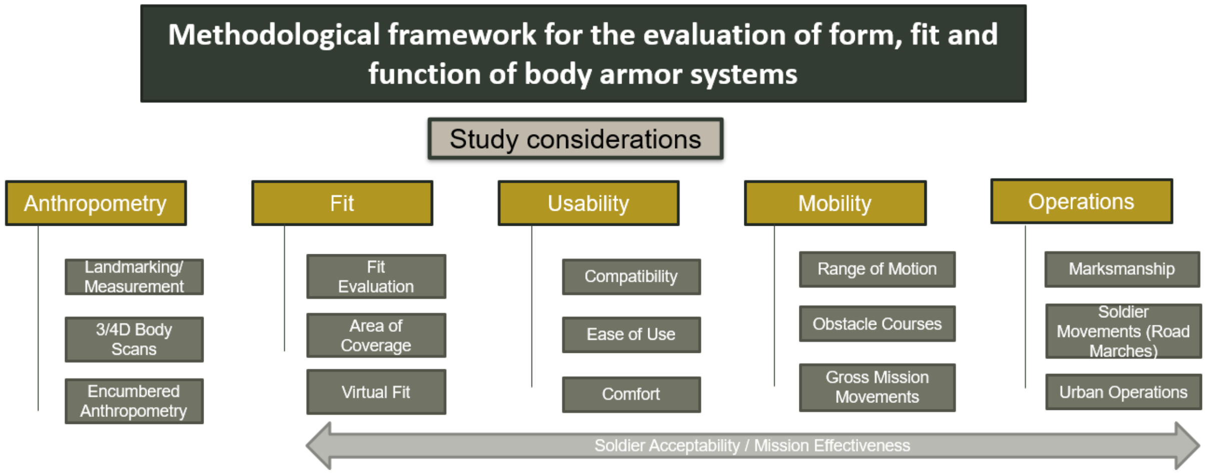


Figure 1: Overview of the methodological framework.

CONSIDERATIONS

When conducting BA system evaluations, several considerations must be discussed during the design phase of the effort. These include:

- Study goals
- Participant population
- Evaluation methodologies
- Metrics
- Resources
- Safety

Study goals

It is necessary to first determine the size, scope, and evaluation instrument that will best accomplish study goals and answer research questions. Is the study a quick-look at a single-size, early-stage BA system prototype? Is the study evaluating the complete size range of a BA system for a customer? Or is the study a full-scale research evaluation, exploring specific research questions and hypotheses requiring Institutional Review Board (IRB) review? Each type of study calls for the consideration of varied criteria for success, which are discussed in the following sections.

Participant population

The type of study will determine the participant population. Key considerations include how many participants are needed, who the participants are, and what participants are expected to do.

Quick-look evaluations require a small number of participants (n= <10) for identifying preliminary form, fit, and function issues. Participants can be anyone who fits into the prototype(s). When evaluating a full range of test items or specific customer products, understanding the anthropometric variation of the sample population is important, and it is best practice to have a substantial group of participants who fit within each size of the test item(s). For such a study, it is recommended to have a minimum of five participants per test item size to provide an estimate of size variation within each size, although the more participants that can be captured during an evaluation, the more applicable the results will be. For human factors (HF) evaluations, a smaller total number of individuals (n= 10-15) are generally required to identify form and function issues arising from the test item(s).

In many cases, it is important to include participants that reflect the intended user population, as they provide critical insights otherwise unavailable. For example, when evaluating a Navy BA system, researchers should use Navy participants with relevant work experience. This can aid in understanding how Warfighters approach the specific operational tasks that are required while wearing protective equipment.

Anthropometric best practice requires minimal clothing (males in shorts and females in shorts and a sports top), potentially leaving participants physically and psychologically vulnerable during measurement. Evaluation best practice includes conducting operational tasks in both a baseline system and the test item(s). Baseline and test systems should be similarly sized/fit to the body, appropriately aged/laundered, and worn with parallel equipment/ancillary items. Participants are asked to sit and stand in awkward positions, as well as repeatedly perform operational tasks, which can be time-consuming and fatiguing. When designing BA system studies, consider what you are asking participants to do, what level of discomfort or anxiety they may feel, and how your behavior during evaluations can alleviate their stress.

Evaluation methodologies

Following standardized methodologies enables the capture of required measurements for assessing form, fit, and function. This allows for comparisons across test conditions and different evaluations. Hotzman et al. (2011) is a good resource to review when it comes to collecting basic anthropometric measurements. When trying to capture similar measurements with participants wearing equipment, equipment modifications are often required to meet standard anthropometry methodology and capture the required measurements (see Paquette et al., 1999; Garlie and Choi, 2014). In addition, many of the HF measurements are research measurement standards that have been modified to capture mobility and range of motion while participants are wearing BA systems and ancillary equipment (see Mitchell, 2013). A detailed review of BA system anthropometry and fit assessment along with a discussion of HF methodologies to understand Warfighter-BA system interactions are discussed later.

Metrics

In general, use anthropometric dimensions that are related to the test item(s) being studied. For BA systems, torso measurements are of primary interest, as they comprise critical sizing variables and help define the torso's form (e.g., chest girth, underbust girth, waist girth, bustpoint-to-bustpoint breadth, chest depth, back waist length, etc.). Stature and weight are useful for describing the sample population relative to the larger population. A detailed description of these and more anthropometric measurements can be found in Hotzman et al. (2011).

If three-dimensional/four-dimensional (3D/4D) scanning procedures are used, then it is important to define the body form descriptors of the sample that aid in understanding overall BA systems fit. When employing 3D/4D scanning, it is important to define key body geometries (e.g., torso curvature, shoulder shape, and chest shape) and/or movements of interest (e.g. reaches, or shooter positions (standing, prone, or kneeling)).

Human factors methodology evaluates mobility measurements for various joints or joint systems (e.g., cross body reach, sit and bend, and head rotations). Additional analyses focus on how the BA systems move on or restrict the body while performing specific operational tasks (e.g., shooters positions (standing, kneeling, prone), grenade throws, room clearing). Mobility measurements, joints, and operational tasks should be defined before beginning the evaluation.

Resources

Necessary resources are determined by the type of BA system evaluation performed. Quick-look evaluations may require a single prototype, measuring tools, the researcher, and a couple of participants. This type of evaluation may only take a couple of hours.

However, when assessing a range of BA sizes or systems, often a team of researchers with access to a large number of participants is required. These multi-day efforts may require travel to access the necessary participants and must include every available size of the BA system(s) being studied. It is also critical to have access to the intended sizing system and any manufacturer's definition of fit, although they are not always available, and assumptions sometimes need to be made regarding the critical sizing variable(s) for each system. Measurement stations should include a trained measurer and a trained recorder for data integrity.

Safety

In general, undertaking anthropometric and HF procedures poses little or no danger to either participants or measurers, but care should always be taken to reduce the risks to both. The following tips can help provide a safe measurement environment:

- Do not poke or jab a participant with the blades of an anthropometer or caliper.
- When using a 3D/4D scanner, explain the technology and any associated risk levels to participants.
- Pay attention to participant body language as they are being measured or getting on or off measurement platforms and be prepared to assist them in case they stumble or fall.
- Understand that a participants' normal center of gravity is altered when they are wearing BA systems, and that the added weight can increase heat stress, rubbing/chaffing, and general discomfort.
- Be sure to offer participants rest breaks and remind them to stay hydrated so that they do not become overheated or faint.
- Do not drop test items on the participant as they are changing in and out of the system(s). For some HF evaluations, participants wear BA systems and kit while conducting simulated operational tasks in the lab or actual tasks in the field. Care should be taken to ensure participants maintain awareness, so they are not injured while conducting these tasks.
- Be aware of any quick-release functionality in a test system so that you can prevent participants from inadvertently activating the release function, which can quickly drop parts of the system onto evaluators or participants.
- Always maintain good sanitation practices. Testers should have antibacterial lotion, wipes, and/or alcohol swabs to keep hands free of germs. In addition, test equipment should always be wiped down, laundered, or otherwise disinfected after each measurement session/participant.

PERFORMANCE METRICS: ANTHROPOMETRY AND HUMAN FACTORS

This chapter provides an overview of the anthropometric and human factors engineering strategies that will improve BA system form, fit, and function knowledge. This guidance can be modified depending on the type of study (e.g., laboratory-based vs. a field test).

Anthropometry

Understanding BA system fit requires accurately describing the Warfighter population's overall shape and size (i.e., anthropometry). This section provides an overview of the anthropometric methodology that enables BA system design, development, and fit assessment. This overview describes the measurement instruments and test procedures used to determine BA system fit.

A note of caution - before conducting any BA system evaluations, participants must be outfitted in their best available BA system size. If participants are not wearing a properly sized BA system, their performance results should be considered flawed. Work by Choi et al. (2016; 2018) exploring the relationship between BA system fit and Warfighter performance found that inadequate fit can negatively impact performance or safety by either reducing overall mobility (BA system that is too large) or by reducing overall BA system coverage (BA system that is too small).

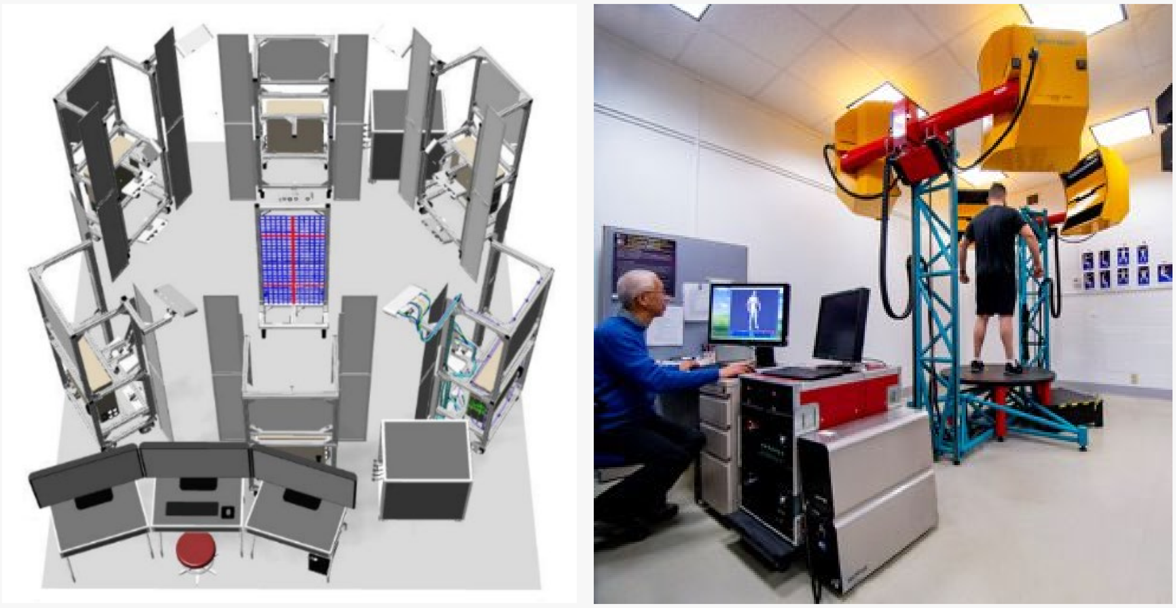
Measurement Instruments

This method uses standardized measurement tools that the military has employed to collect anthropometric data beginning in the 1940s, following World War II, to characterize the size and shape of the military force to develop clothing and individual equipment, and vehicle and workstation design (Figure 2).

1. Anthropometer: A GPM Swiss-made anthropometer is used to collect standing and seated linear body measurements.
2. Digital Scale for recording weights.
3. Anthropometric footbox, modified Brannock device, or other calibrated device for recording foot dimensions.
4. Poech Caliper for measuring hand lengths.
5. Tape Measure: A Lufkin 2m steel tape is used to collect body circumference measurements.
6. Spreading caliper for measuring head breadths and lengths.
7. Sliding caliper for measuring shorter body length and breadths (e.g., face, hand, and foot).

These instruments have been selected due to their high precision of accuracy and have shown not to degrade in performance after extended use. All body measurements are recorded to the nearest millimeter except weight, which is measured to the nearest 10^{th} of a kilogram using a SECA digital scale. Additionally, 3D and 4D scanning systems (Figure 3) can be used and are discussed later.

Figure 2: Standard anthropometry equipment: 1. Anthropometer, 2. Scale, 3. Foot Box/Modified Brannock Device, 4. Poech Caliper, 5. Tape Measure, 6. Spreading Caliper, 7. Sliding Caliper.



1. 3DMd whole body

2. Cyberware WBX whole body

Figure 3: 3D and 4D whole-body scanning systems. 1. 3DMd, 2. Cyberware whole body scanner

For capturing the size and shape of participants who are wearing BA system(s) and ancillary equipment, some modifications of the standard tool kit are necessary (Figure 4).

1. Extended anthropometric blades. Used to obtain linear measurements of the equipped participant that standard anthropometric blades are too short to provide.
2. Modified tape measure: A modified 2m tape with a tension spring allowing for measurement with a constant tension of 80 g.
3. Modified anthropometer: A modified anthropometer with a laser level and a wheeled base to assist with transferring measurement location landmarks during equipped conditions.

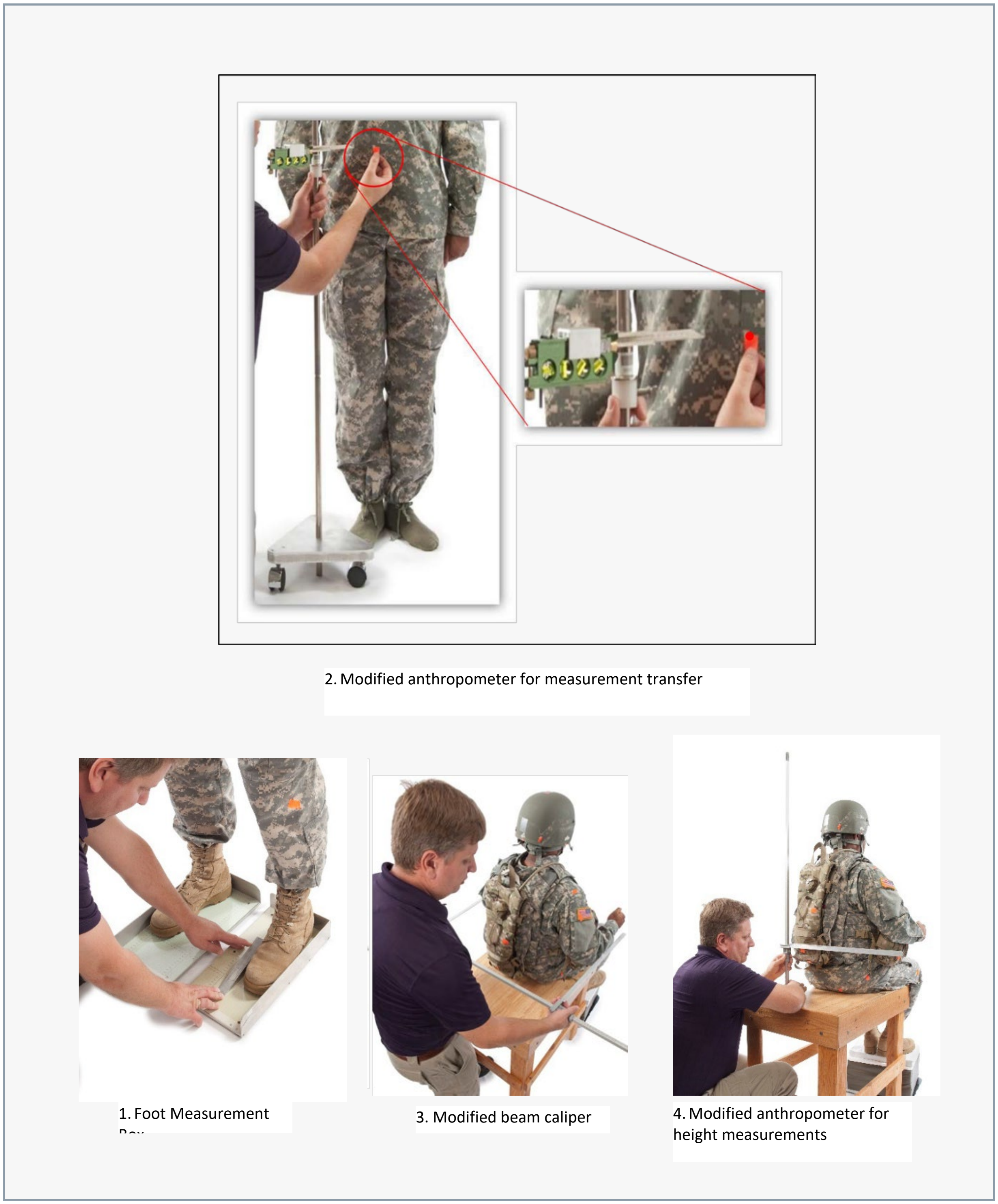


Figure 4: Modified anthropometric tools for measurement of encumbered participants: 1. Foot measurement box, 2. Modified anthropometer for measurement transfer, 3. Modified beam caliper, 4. Modified anthropometer for height measurements.

Test Procedures

Anthropometric BA system testing can be divided into four primary stations, with a fifth station if using 3D/4D scanning: 1) Briefing, 2) Landmarking, 3) Measuring and fitting, 4) Scanning, and 5) Out-processing. All measurement stations are manned by a team: a trained measurer and a trained recorder. These stations may be merged, or there may be multiple lanes of each station depending on the study's size and throughput. Because participants may move through the measuring and scanning stations in any order, every study must incorporate a checklist (either on paper or electronic) that updates as the participant progresses through the study. When incorporating HF assessments into the study, after the participants have completed the anthropometric testing, they then move to the HF stations and undergo testing. A common example of a study progression is presented in Figure 5. This progression can be easily adapted for use in other studies.

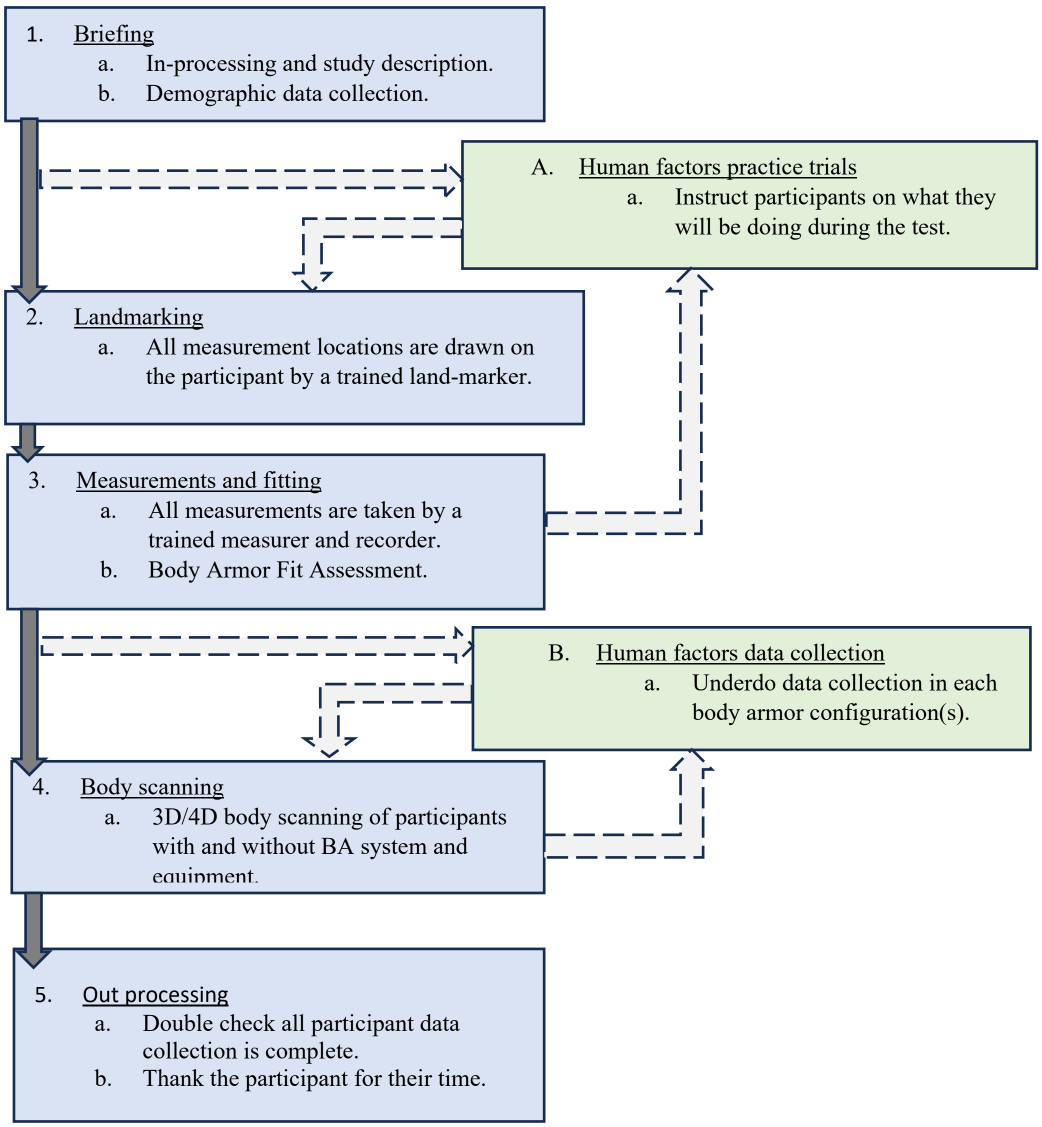


Figure 5: An example of the order of testing for BA systems

Briefing: When participants arrive at the testing area, they are briefed on the study's purpose, what they will be doing during the evaluation session, and their right to withdraw from the study at any time without repercussion. At this time, participant consent is obtained, and participants are given a demographic questionnaire. The questionnaire gathers information about their military experience, demographics, and BA systems experience. Participants are then asked to change into gender-specific measurement clothing: shorts for male participants and shorts and sports top for female participants. They are then landmarked, and baseline anthropometric measurements are captured.

A note of caution – Due to privacy or comfort reasons, in field situations it may be difficult to have participants change into measurement clothing. Instead, it may become necessary to collect data with participants wearing t-shirts, duty uniform trousers, or other easily available types of clothing. In these field situations, try to maintain standardized measurement methods while working around these clothing challenges.

Landmarking: Once participants have completed the briefing and have donned measurement clothing, they are landmarked at specific body locations using non-allergenic marking instruments, usually a make-up pencil or a surgical marker. Most landmarks are located by sight or palpation of a body location. Some landmarking requires the use of a landmark transfer rod, 2m steel tape measure, a straight edge with level, and a variety of plastic or metal rulers. A detailed description of how to find and mark the most common anthropometric landmarks is available in Hotzman et al., 2011. Each study should identify and define the measurement selection before beginning. For example, torso-borne BA systems would require a selection of torso measurements. In addition, if employing 3D/4D scanning, then half-inch adhesive dots (colored, to be easily detected by the scanning system) can be placed over some of the already highlighted landmarks to allow for better visibility and identification of these landmarks on the scan. These adhesive dots can also be placed on the participants' duty uniform and BA system to capture the required body region locations (i.e., Chest Point, Omphalion, etc.) when fully equipped.

Anthropometric Measurements: Once landmarking is completed, researchers collect anthropometric measurements at specific body locations. These body measurements are generally divided up into standing and seated measurements when necessary and are conducted in a strategic logical order to minimize the workload of both the measurer and the test participant. When conducting anthropometric measurement evaluations, it is critical to be aware of measurement error and ways to provide accurate measurements. First, researchers should be aware of the parallax effect, or the apparent displacement of an object owing to the angle from which it is viewed. This can be a significant source of error in anthropometry, and the anthropometrist must endeavor to have their eyes at the same level as the measurement termination landmark or at the level at which the measurement is being taken. For measurements taken on the lower body, participants can stand on a platform, but it will still be necessary for the measurer to do some amount of bending or stooping to bring their eyes in line with a landmark, the blade of an instrument, or a tape measure. A stool or ladder can be used for assistance when certain measurements are required, and the participant is significantly taller than the measurer (e.g., Stature). Secondly, it is critical for the researcher to take repeatable and reliable measurements during any evaluation, as anthropometric data are only as good as the repeatability and reliability with which the body dimensions are measured. The position of the body, the amount of pressure exerted on the instruments, and breathing cycles are only a few of the sources of variation that can seriously affect the repeatability and reliability of the measurements. For a detailed description of pitfalls of measurement reliability and repeatability, it is strongly recommended to review the U.S. Army Anthropometric Surveys handbooks for measurement methodology (Clauser et al., 1988; Hotzman et al., 2011). These handbooks highlight the instructions, the goal of practical training, and standardizes the way these dimensions are measured to reduce measurement variations. A list of allowable interobserver errors and how they were calculated is also described within. Additional sources describing measurement practices and how to obtain measurements on the fully equipped or encumbered test participants can be found in Choi et al. (2014), Garlie and Choi (2014), Paquette et al. (1999). Remember that it is important to have both trained measurers and recorders for data integrity. Data recorders not only record the measurements but serve as the measurer's second set of eyes to ensure the participant is in the proper position and that the measurement equipment is in the correct alignment for capturing an accurate measurement.

Scanning: When digital scanning is used in a BA system evaluation, the researchers must decide between a laboratory-based scanning system and a field scanning system. If field scanning is required, then the type of scanners will need to be determined. When the study is large enough, it could warrant shipping a full-size laboratory scanner to the site. If not, there are less accurate, portable systems, to include hand-held scanners, that can potentially answer the questions of interest. All scanners have pros and cons attached to them that should be considered during the planning stages of the evaluation (cost, portability, quality of scan, accuracy of data).

Scan postures may differ between studies due to study requirements and scanner capabilities. Common scanning postures for BA systems assessment include (e.g., A-pose, T-post, sitting pose, etc.). In field studies where a whole-body scanner may not be available and a hand-held scanner is used for time expediency, scanning would only include the torso area and not the whole body.

Recent advances in scanning technology include the ability to capture the motion of the participant being scanned. This 4D method of scanning can capture individuals moving from one posture to another at actual speed, allowing for the analysis of the data to look at how body movement and equipment integrate. For example, a participant wearing a BA system with a weapon can go from a standing weapons-ready position to a kneeling weapons-ready position to a prone weapons-ready position. Analysis of this data will provide critical information as to how the BA system moves with the body as the participant goes through these motions in real time. Understanding how the body and/or fit of the armor changes during these dynamic movements is a critical issue in BA system research.

<u>Scanning Steps:</u>

1. Scanner Calibration: Prior to beginning any scanning session, an initial calibration process of aligning and coordinating the scanner sensors is required. Calibration must occur when the scanner is first set up, and then periodically afterwards to maintain proper sensor alignment and coordination (Ashdown, 2020).
2. Baseline Scan: Whole-body scanning sessions require participants to wear appropriately sized scanner apparel, which must be free of wrinkles. The outfit should lie smoothly against the skin but not so tight that it compresses the skin (e.g., a tight waist band).
3. BA System Scan: The participant dons their duty uniform and BA system for a series of assessment scans. These scans are repeated for each of the identified BA system configurations for the study.
4. Scan Storage: 3D/4D scans should have a common naming convention so that they can be organized and stored on the computer for easy access.
5. Scan Cleaning: All scans will need to be post-processed for cleaning and preparing them for use in study analyses.

Out-processing: Once all participant tasks are complete, they will proceed to the out-processing station. A team member will review the participant's checklist to ensure that they visited all required measuring, scanning, and HF assessment stations. If not, direct them to the missing station. If all information is complete, ensure the participant has returned all equipment, then thank them, and dismiss them from the study.

Fit assessment

Assessing BA system fit requires clearly stating the fit assessment goals upfront and includes:

1. Mobility and performance and comfort
2. Body armor improvement
3. Critical assessments
4. Virtual fit assessments

Mobility, Performance, and Comfort. After collecting the necessary anthropometric measurements, the best-fitting size from the BA system sizing chart is selected for each participant. Select the best-fitting size using the size chart's key sizing variables (e.g., Chest Circumference for upper torso products). If a size chart is not available, estimate a predicted size using an available legacy sizing chart for similar clothing and individual equipment (CIE) or from the current size of a test participant's duty uniform.

The test participant dons the predicted best-fitting BA system size while the assessor evaluates the BA system fit using specific fit criteria outlined by the vendor, plus any additional criteria designed by the assessor. The assessor evaluates the positioning and coverage of the ballistic plate and soft armor on the test participant in standing and seated positions, as well as during several basic movements (jumping, kneeling, squatting, stepping up and down, etc.). The assessor notes how well the selected size fits and conforms to the test participant's body. Elicit the test participant's feedback on areas of discomfort, poor fit, mobility, and overall likes and dislikes of the BA system fit.

Since predicted sizes are an estimation tool, this assessment process repeats with adjacent BA system sizes to identify the true best fitting BA system size. The true best-fitting size, as determined by the SME, should provide appropriate chest coverage and protection relative to torso width and length, plus maximum mobility, performance, and comfort. If no size provides adequate coverage or severely impedes mobility, performance, or comfort, record "no fit" for that participant. For reporting purposes, it may be necessary to note that the best fitting size may not be a perfect fit or may have issues at specific body areas when determining whether that size is "acceptable" or "unacceptable". Figure 6 provides an example of a data collection form, which can be modified to meet the specific needs of any fit assessment for mobility, performance, and comfort.

Area	Rating		
	Big/Loose/High	OK	Small/Tight/Low
Neck Opening	☐	☐	☐
Front Yoke	☐	☐	☐
Back Yoke	☐	☐	☐
Chest	☐	☐	☐
Shoulder/chest/back area	☐	☐	☐
Shoulder Straps	☐	☐	☐
Waist	☐	☐	☐
Front Length	☐	☐	☐
Back Length	☐	☐	☐
Front Plate	☐	☐	☐
Back Plate	☐	☐	☐
Side Plate	☐	☐	☐
DAPs	☐	☐	☐

Figure 6: Sample data collection form

Improvement. These BA systems are usually in an early developmental stage where there could be a single size or multiple sizes. For this effort, the goal is to assess BA system fit, determine the range of body sizes that would be accommodated by the prototype(s), and provide fit and sizing accommodation feedback to the designers. At this stage, aim to suggest design modifications for optimizing prototype(s) fit across a range of body sizes. For example, when evaluating a single "medium sized" BA system prototype, determine the minimum and maximum body size range accommodated by that "medium sized" prototype and document any specific issues with mobility, performance, or comfort arising from testing. This information enables grading scheme development, where designers build larger and smaller sizes of the prototype. Iterative improvement analyses help designers optimize prototype fit before executing mass-production.

Critical Assessments. Specific features of BA system body coverage are critical for the assessor to record because they may impede mobility and performance and cause discomfort (Figure 7).

1. The rigid front ballistic plate should cover the torso from 1" or less below Suprasternale (#1 in Figure 7) to 1" or less above Omphalion (belly button) (#4 in Figure 7). The assessor should verify any manufacturer's information regarding plate location, but most rely on the fact that the hard armor plate is required to cover the vital organs.

2. The bottom front of the carrier system (i.e., soft armor portion) (located below #4 in Figure 7, not shown) should be located below the Omphalion but not so low as to touch the thigh when the participant is in a seated position, nor impact the Warfighter's ability to bend at the waist.

3. The width of the front plate should adequately cover the torso from Thelion to Thelion (nipple to nipple) and should be no wider than the rib cage (#3 in Figure 7). This location can be determined by palpating the rib cage. Again, assessors should refer to the manufacturer's guidelines for hard plate location. Plates that are at the edge or wider than the rib cage should be considered too wide on the torso and may impact certain mobility tasks (Choi et al., 2016; 2018).

4. The rigid back ballistic plate ideally covers the torso from the 7th cervical vertebrae (C7) to the level of Omphalion (#2 in Figure 7); however, previous experience suggests that the actual top of the back

carrier is generally parallel to the top of the front carrier when viewed from the side and rarely covers C7.

5. If evaluating the fit of a BA system with side ballistic plates, these plates should be horizontally and vertically centered on the side torso of the test participant (#5 in Figure 7). Ensure the top edge does not dig into the soft tissue of the chest or the underside of the upper arm and that the bottom edge does not dig into or rub the hip bone or any soft tissue around the waist.

6. Lastly, consider the amount of soft armor coverage around the front, back, and side ballistic plates or at the location of the shoulders, neck, and sides of the BA system, as deemed required for overlap of different components of the specific systems (not shown).

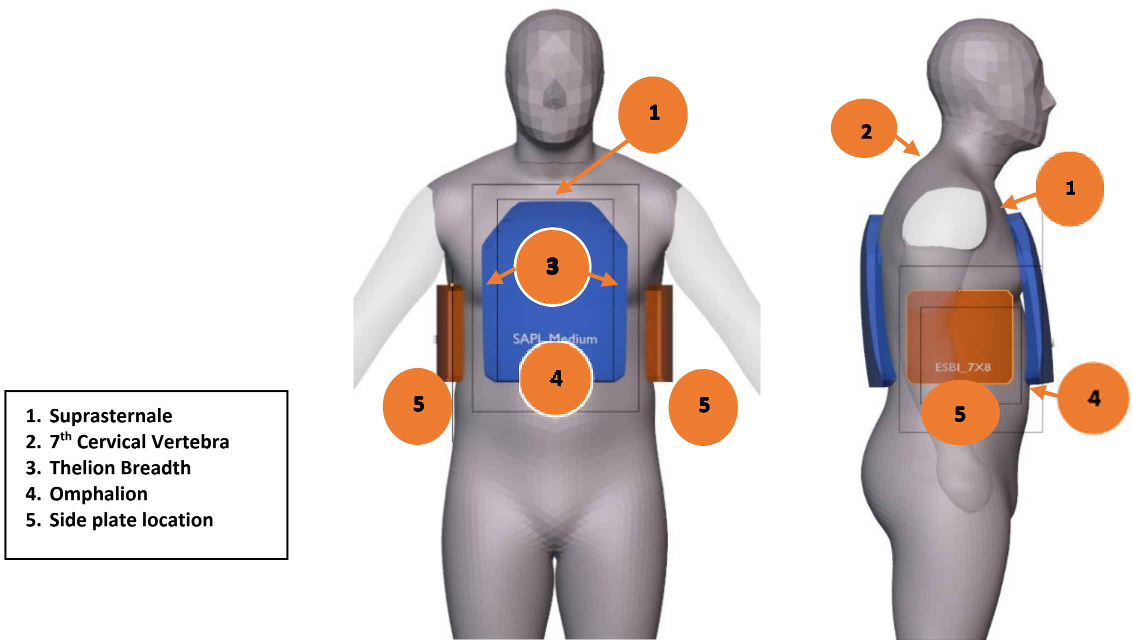


Figure 7: Body armor placement

Virtual fit. Recent efforts have started to explore 3D/4D fit assessments of BA systems and equipment: virtual fit. Virtual fitting simulates physical fit assessment methodologies using digital modeling of items and participants. Typically, a digital version of the prototype(s) interacts with a digital human model to assess how well the prototype fits that person. Fit may be assessed by a human evaluator or via machine learning and artificial intelligence. In some cases, the digital human model is dynamic and can "move" into a variety of different postures, potentially providing additional feedback on the fit beyond the static assessment.

The virtual fit assessment process has the potential to be an efficient methodology for quickly processing BA system fit at a population level using large whole-body scan databases without engaging in expensive field evaluations. Virtual fitting technology has recently been adopted (Ashdown et al., 2004; Lee, 2014; Lin and Wang, 2016), with multiple available commercial software products (e.g., Lectra, Optitex, Browzwear, Clo3D) offering virtual fit assessments and donning simulations. While virtual fitting appears to be a quick and easy solution for fitting prototypes, it is still in its infancy, requiring a large amount of front-end work to set up, with limited accuracy validation. Virtual fitting accuracy is likely highly dependent on the prototype's characteristics, the digital model's precision (especially fabric characteristics), boundary definitions, and the accuracy and completeness of AI training models (Ashdown et al., 2004). When fabric characteristics accurately simulate clothing drape, these software products may truthfully simulate the BA system-Warfighter interaction. Non-fabric items that do not wrinkle, such as hard armor plates and helmets, may provide fewer challenges to the development of virtual fitting assessments (Choi et al., 2009).

Figure 7 provides an example of a visual alignment of hard armor plates relative to a 3D whole-body image. However, it is challenging to visually assess the intricacies of fit and interaction of the plate with the body. Because the plate is rigid, it does not fold and drape as it interacts with the body but can poke and/or compress at isolated points or the surface area of the plate and therefore the angle of placement and compression of the soft tissue becomes important in determining the overall acceptability of fit. In addition, the virtual body does not react the same way as a real body and creates difficulties in the understanding of fit and comfort. In Figure 7, for example, the plates were manually aligned with a maximum skin compression of 20 mm; however, the results are currently limited because of the limited information possessed regarding soft tissue compression related to the wearing of protective equipment. Currently, virtual fitting offers no subjective feedback and is solely reliant on the researchers' judgement of where the plates are located on the body. Based on this visual presentation with limited data and whether the fit is acceptable or not, the ability of machine learning to be trained is still uncertain.

Human Factors

Human factors assessments are a critical component of evaluations focused on the form and function of the BA system and how the user interacts with it. This section provides an overview of the human factors methods that support BA system design and development, as well as BA system fit. This overview outlines several components for evaluating the impact of the BA system on the user, with multiple examples of recommended activities. The list is by no means all-encompassing. Remember that if participants are not wearing a properly sized BA system, any performance-related results from other assessments should be considered flawed.

Most human factors metrics typically include both objective and subjective scores. For best results, it is critical to run a comparative study where participants execute the evaluation tasks in a minimum of 2-3 conditions: a baseline condition, usually their duty uniform alone (for objective measurements only); when the participant wears the currently issued item (if one exists); and when participants wear the test item BA system. The focus of these evaluations includes metrics such as:

- Ease of use: how easy it is to don/doff and adjust the system; how difficult is it to operate special features, such as emergency egress?
- Compatibility: how well does it interface with other clothing, equipment, and environment/platforms?
- Comfort: identification of points of discomfort both initial and after longer term wear. This can encompass both physical comfort and thermal comfort.
- Safety and health hazards: anything that may cause a safety issue (e.g., snags) or a health hazard (rubbing/chafing that can open the skin).
- Signatures: does the system create any type of audio, visual or thermal signature that may put the user at risk?
- Reliability and durability: how reliable and/or durable are the systems, is it likely to break, or can it withstand the rugged nature of most field operations? If it breaks, what are the consequences?

- Functionality/impact on mission: does the system do what it's supposed to do and does it impact the user's ability to complete their mission (either partially or fully)?
- Soldier/user acceptability: would the Soldier be willing to use it?

Several decisions regarding how the BA system should be worn must be made prior to testing; these decisions are driven by the study goals. First, decide which BA system components should be worn during each phase of testing (e.g., should the plate be worn or just the carrier, should side plates be included, should ancillary items such as the yoke and collar be worn). Chosen BA system components will vary depending upon the different tasks being executed as part of the study.

Second, decide if the BA system will be worn with additional mission equipment or as just a vest alone. If participants will wear mission equipment (e.g., magazines, grenades, water, first aid kit) as they complete the test tasks, decide which equipment to include and where it should be mounted on the body/BA system. Determine if all participants will wear the same thing or if what is worn will vary based on TP preferences and duty position. For operational tasks, participants often wear a standard rifleman load regardless of their duty position. This ensures standardization, repeatability, and a high level of control required by scientific research while balancing the operational realism of the task. In instances where the focus is on assessing the impact of the armor system on movement, participants complete the task in the bare or "slick" BA system (i.e., without mission equipment or kit).

Third, the experience level and demographic makeup of the study population needs to be considered. In some cases, a convenience sample is used due to ease of access and limited resources. In other cases, it becomes important to have users with experience wearing BA systems for a substantial amount of time. Other important demographics to consider are the military job occupation series, subject's body size, and whether they are male or female participants.

Usability and Agile Design Assessments

Usability and agile design assessments should be executed early in the design process, requiring only a single prototype. The goal of these types of assessments is to find and address high level issues so that the design team can quickly develop alternative design solutions. These assessments are frequently completed in conjunction with the designers and/or the project officers. Testing with each participant usually takes between 1 and 4 h.

Three to five participants are assessed individually while performing a variety of basic mobility and mission tasks. Donning, doffing, adjustability, compatibility, ease of use, impact on mission performance, mobility, acceptability, and fit are key metrics. Specific activities are customized for each individual test item. For example, in the case of a BA system, activities focus on tasks related to upper body mobility (e.g., sitting, bending at the waist, box lifts, overhead maintenance, aiming weapons in the standing, kneeling and prone postures).

Most findings are focused on test team observations and participant discussions. Findings lead to identifying necessary critical design changes early in the development and acquisition process, without incurring significant costs. By integrating human factors and anthropometry expertise into the assessment, project officers, designers, and engineers can see and hear participant feedback firsthand, allowing them to leave with an understanding of issues and ideas for how to fix them. Written summaries of the results of the assessment and its findings are provided following the completion of the assessment, providing project and design documentation.

Compatibility

Compatibility is the degree to which a system integrates or interferes with other equipment, clothing, or the environment (e.g., vehicle, aircraft, wooded terrain). Assessment of compatibility is usually conducted in a pass/fail manner using tester observation and input from the participant. While assessing system compatibility within an environment usually requires extended issue and wear trials or human factors evaluations, compatibility of clothing and equipment systems can easily be evaluated as part of a usability/design assessment.

Compatibility is normally assessed during extended issue and wear trials as the participant encounters companion items, and it is important to use a range of participant body sizes for this activity. For example, a compatibility issue for users in one size or at the bottom end of an adjustable size may not be the same issues for those in a different size or at the top end of the adjustability. During human factors trials, a compatibility assessment can be actively directed. Participants don relevant clothing and equipment, and then conduct a series of basic tasks to discover if any issues occur. Close up photos are especially useful for documenting issues that may be difficult to explain verbally.

BA systems should be tested with duty uniforms, gloves, environmental clothing, rucksacks, load carriage systems, helmets, ancillary BA system components (groin, shoulder protection, yoke/collar protection) and kit that would normally be worn on the BA system (magazine pouches, medical kits, tactical load carriers, grenades, hydration, radios, pistols, etc.). This list can become quite extensive, especially when analysis involves specialized equipment.

Comfort

Comfort is a critical metric in BA assessment that relies on the test participant's impressions. While Likert or visual analog scales can be customized for each BA assessment, validated standardized scales are also available (Figure 8). Wearable sensors advancement is expanding at a rapid pace, and wearable pressure or load sensors appropriate for quantifiable BA system assessment may soon be available.

Comfort is often closely linked with health hazards and injury issues (e.g., skin abrasions, rubbing/chafing, hot spots), but can also be associated with item weight and weight distribution. As comfort can change over time, it is important to consider both initial and extended comfort. Extended wear can turn a sensation that seems tolerable initially into an irritant, for example when the hard armor plates rub against bony areas of the body (e.g., collar or hip bone) or pinch soft tissue.

Thermal comfort and sensation are additional types of comfort that should not be overlooked; this is the perceived comfort from a user of how hot they are due to wearing the equipment. Design features that increase breathability may increase thermal comfort, but there is a tradeoff between breathability and protection. There are multiple skin-temperature estimating sensors, but they have not been fully validated for BA system assessment.

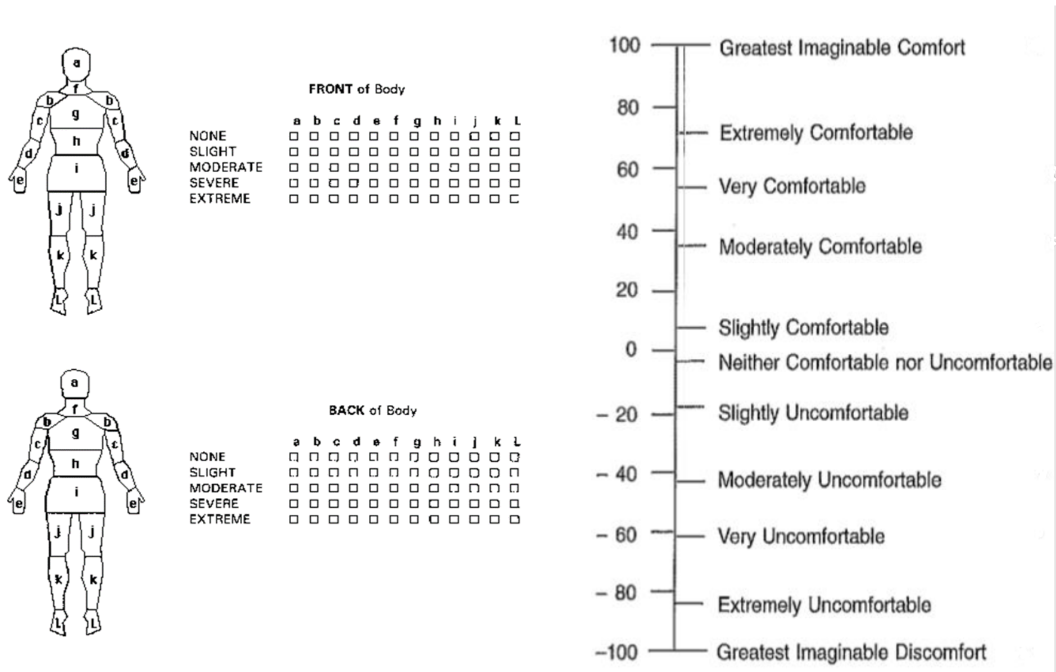


Figure 8: Example of comfort scales: Rating of Pain, Soreness and Discomfort (RPSD) scale with full human anatomy (Courtesy of Corlett & Bishop, 1976) (left); Comfort Affected Labeled Magnitude (CALM) scale (Courtesy of Cardello, Winterhalter & Schultz, 2003) (right)

Mobility

Mobility can be assessed both objectively and subjectively, depending on the goals of the effort and the resources available. Mobility focuses on the ability of the participant to move. Ideally, subjective, and objective measures would be used together. With the increase in affordability, accuracy, and availability of wearable devices, the ability to incorporate physiological data into mobility assessments has improved. Additionally, inertial measurement unit (IMU) devices can increase the objective data being captured from mobility tasks, especially as more algorithms for interpretation are developed by exploring the deltas between BA system movement and body movement for these mobility tasks.

Mission Task Based Obstacle Courses

The Load Evaluation Assessment Program (LEAP) (see Figure 9) is an example of a standardized obstacle course that can be used in whole or in part to aid in the evaluation of BA system(s). During LEAP evaluations, participants navigate through the obstacle course in different test conditions. For LEAP assessments, always include a baseline condition (e.g., duty uniform with addition of helmet, gloves, and/or knee and elbows (if deemed necessary for safety reasons). The LEAP captures a participant's completion time for the whole course and individual obstacles. In addition, vertical jumps, load transfers, and marksmanship tasks can be assessed pre/post the LEAP obstacle course to better understand the effects of fatigue related to the equipment.

Current completed research with different BA systems using the LEAP has shown that weight is the primary driver of time performance, both at the overall and the obstacle level (Batty et al., 2016; Mitchell et al., 2016), although bulk does have an effect as well at the extremes (Mitchell et al., 2018). During LEAP testing with BA systems, additional sensors can be added to measure participant heart rate (and related measures), breathing, acceleration, and to identify predictors of injury. The subjective data from this testing can provide more significant design guidance for BA system design and development than the timing results can (Davis, 2017; Dutton & Styker, 2016; Dutton & Styker, 2015; Brewster, 2014).

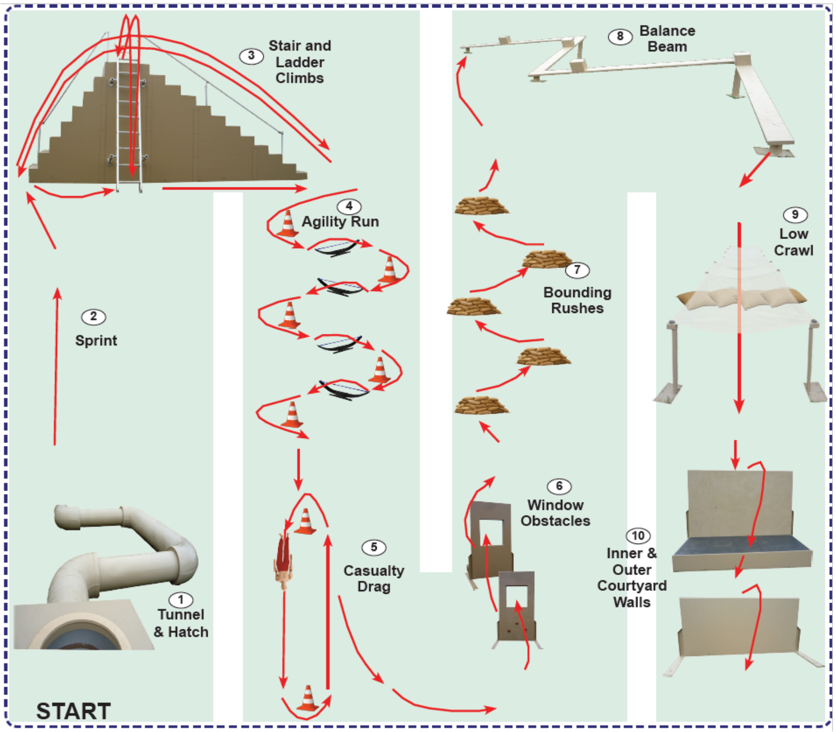


Figure 9: LEAP obstacle system layout

Range of Motion (ROM)

Range of motion (ROM) is either measured at relevant body joints (e.g., neck, shoulder, hip) or at the point where a participant has extended a limb or part of the body to its maximum displacement. ROM at body joints is measured using goniometry. For joints, ROM is the maximum angular deviation at the joint and expresses joint mobility. The range of joint motion is measured at the angle formed by the long axes of two adjoining body segments (such as the femur and tibia), or by one body segment and a vertical or horizontal plane. The maximum extent of ROM is measured between the two extreme positions of the joint. Limb extension ROM is measured by the distance reached by the limb, usually from some reference point such as a wall, floor, or other fixed landmark. In BA assessment, goniometry is used to assess the change in ROM caused by wearing BA systems (e.g., sitting and bending, cross-shoulder reach, and torso movement. Commonly used terminology (abduction, adduction, rotation, extension, and flexion) applied to joint movement is illustrated in Figure 10.

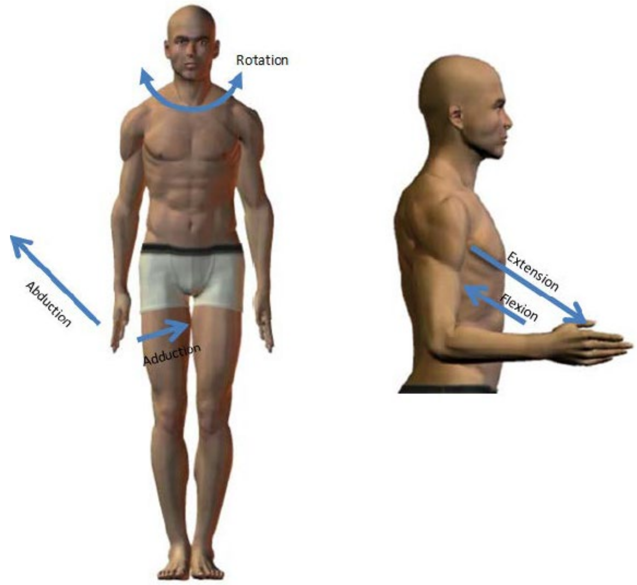


Figure 10: Body movement descriptions: abduction, adduction, rotation, extension, and flexion (images courtesy of Mitchell, 2013)

Several tasks are employed to examine the impact of BA systems on body mobility, or whole-body freedom of movement. These tasks and measurements, as detailed in Mitchell 2013, allow testers to quantify the amount of restriction imposed by a test item by comparing the findings to participants wearing a baseline configuration. These tasks also allow testers to isolate and identify specific aspects of the test configuration that might be contributing to the restricted movements. For these tasks, test conditions may include the BA system alone or BA system plus kit, depending upon the objectives. Note that although the Soldier "kit" includes a helmet, the helmet may be omitted in cases where the BA system performance alone is assessed (for example, when helmet/collar interaction is not a concern because the primary focus is on the fit/sizing aspects of the armor and plates on the torso).

Perform all tasks three times within each configuration and calculate the mean score for each configuration. After performing each set of body movements in BA system configurations, participants rate the level of restriction they felt while performing the specific movement, using standardized rating scales. Figure 11 provides an example of a restriction rating scale.

Restriction Ratings				
No Interference or degradation	**Slight Interference;** easily worked around	**Moderate interference;** difficult, but able to work around	**Severe interference;** very difficult to work-around; unacceptable	**Extreme interference;** unable to work-around; unacceptable
1	2	3	4	5

Movement	**1st**	**2nd**	**3rd**	**Rest Rate**
Cervical Rotation				
Comments:				

Figure 11: Example of restriction rating data collection sheet (images courtesy of Mitchell, 2013)

For BA system testing, movements usually focus on the joints and movements associated with the spine (from lower back (lumbar) to neck (cervicale), hips and shoulders. Mitchell's (2013) report defines a series of these movements, with detailed instructions on how to measure them and a sampling of scores from that study. Researchers must also decide whether the addition of ancillary BA system components are needed during testing to meet specific research goals or in some cases the guidelines for current operations.

Simple/Gross Level Mobility
In addition to ROM and obstacle courses, BA systems can be assessed using a series of basic movement tasks and operational (or mission-oriented) tasks that provide information on gross mobility offered by the systems. Whether both sets of tasks are used depends upon the objectives of the evaluation. There may be cases where the additional rigor of standardized ROM tasks is not needed to assess the armor system. Many of these tasks are used to confirm the ability of the participant to execute Soldier tasks when wearing the BA system(s) and kit; therefore, conducting various tasks in a baseline condition for comparison may not be necessary.

In general, for HF movements, one HF personnel works directly with one participant at a time as the participant performs a series of basic body movements and mission-oriented activities. After each movement/activity, the participant is asked to rate the level of restriction felt while performing the specific movement/task, using a rating scale (see Figure 11). Participants are also asked whether they experienced any discomfort during the activity, to include specifically if the plates caused or contributed to the discomfort or restriction when plates are used. During each task, the observer documents areas where significant openings or bulging of the armor occurred, which could potentially signify a vulnerability in protection. The tester will document what the causes were and/or the participant's comments.

If additional information is required, especially to make comparisons between conditions, questionnaire data can be gathered. After completing the activities, participants can complete short surveys regarding the BA system(s) that they wore during the evaluation, where they can rate specific aspects of the BA systems(s) and the impact on their performance. Typically, ratings use a 5-point scale, but can also use other rating levels (see Figure 11).

Participants can also provide comparative information of the test BA system(s), based on the 'best fit' size they wore, to their current armor system. If the BA system(s) being evaluated is the same as their current system, participants would compare the size they were issued to the assigned 'best fit' test size; if the armor is not the same, they can compare the two BA systems, being sure to note the size of their issued armor. They can also make overall comparisons among the test items and their own armor. These comparisons provide data that help to ensure that the fit and size is optimized as much as possible.

<u>Operational Performance</u>

Body armor must not only protect the wearer but also should impede the performance of operational tasks as little as feasible. Therefore, BA systems should be assessed for impact upon operational performance. The following assessment tasks provide means of gauging BA performance under operational conditions.

Simulated Marksmanship
BA systems can be evaluated with dynamic methods. Dynamic marksmanship tests like the Individual Shooting Scenario (ISS) or variants of the LEAP course provide critical data of BA performance on tasks that mimic parts of real-world operational scenarios.

The Individual Shooting Scenario (ISS)

The Individual Shooting Scenario (ISS) is a test of dynamic marksmanship performance. The ISS measures the Warfighter's accuracy, precision, decision making, stability, and engagement timing. The ISS (see Figure 12) includes equipment such as an FN Expert weapon simulator mounted to a demilitarized M4 carbine with an integrated carbon dioxide (CO_2) recoil simulation system. This system also includes the use of a weapon's sighting system (e.g., M68 Close Combat Optic) mounted to the Picatinny rail system of the weapon. This unit utilizes an infrared (IR) light that reflects off specially designed reflective paper targets or electronic tablets that have reflective technology mounted to them. When the IR beam hits the reflective targets, and the user pulls the weapon's trigger, the results are captured using Nitrous Oxide Systems (NOS) Pro software that detects the vibration of the trigger and provides the x- and y-coordinates for the location of the hit. The optical unit of this system also captures the movement of the muzzle and identifies this movement in the software.

The ISS scenarios can be designed to be stationary, where the participant stays in one spot but transitions from different firing positions (i.e., prone, standing, and kneeling) while firing at targets at different heights and positions, or dynamic, where the participant sprints to a location where they must make a go/no-go firing decision based on target selections. These evaluations are a timed event and can help evaluate different BA system(s) for mobility and performance issues. More information on the methods can be found in Brown et al. (2022). Figure 12 shows one type of scenario, where the participant runs from the initial firing line, cuts at the cut point to the left or right based on the cut direction indicator, and assesses whether to fire (at friendly or enemy targets) displayed randomly on one of six targets in view.

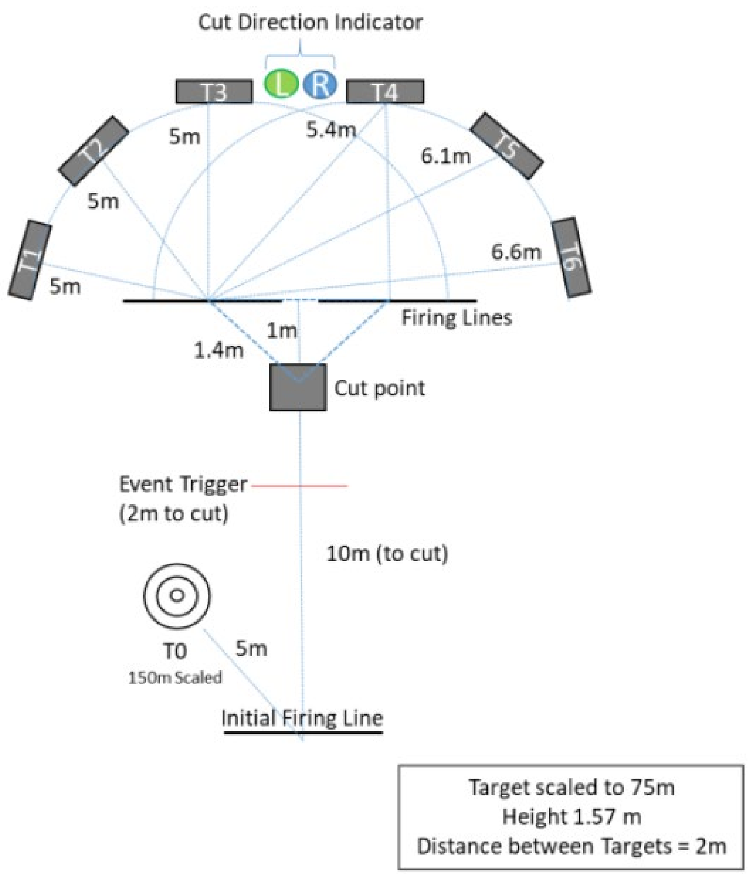


Figure 12: Example of ISS course (Courtesy of Brown et al., 2022)

LEAP – Mobility, Lethality, and Survivability (MLS)

Like the ISS, the LEAP-MLS includes equipment such as the FN Expert weapon simulator mounted to a demilitarized M4 carbine with an integrated carbon dioxide (CO_2) recoil simulation system and a weapon's sighting system (e.g., M68 Close Combat Optic). The LEAP-MLS begins with a static shooting task, where participants shoot three trials of 5 shots at a 100-m simulated distance (15 shots) and a 200-m simulated distance (15 shots), prioritizing accuracy over speed, in standing unsupported and prone unsupported. Upon completion of the static shooting, the participants commence the integrated LEAP-MLS obstacle course (Figure 13). The course contains standard obstacles for assessment of mobility, and 14 dynamic (on-the-move) shooting engagements for assessment of lethality, including cognitive decision making (go/no go) and threat discrimination measures. At five locations, videos are captured that quantify bodily exposure and time of exposure to threats during engagements (survivability metrics). Finally, participants complete a post-static marksmanship session (firing position order same as pre-LEAP). Additional details on the methodology are available from Brown and Mitchell (2019).

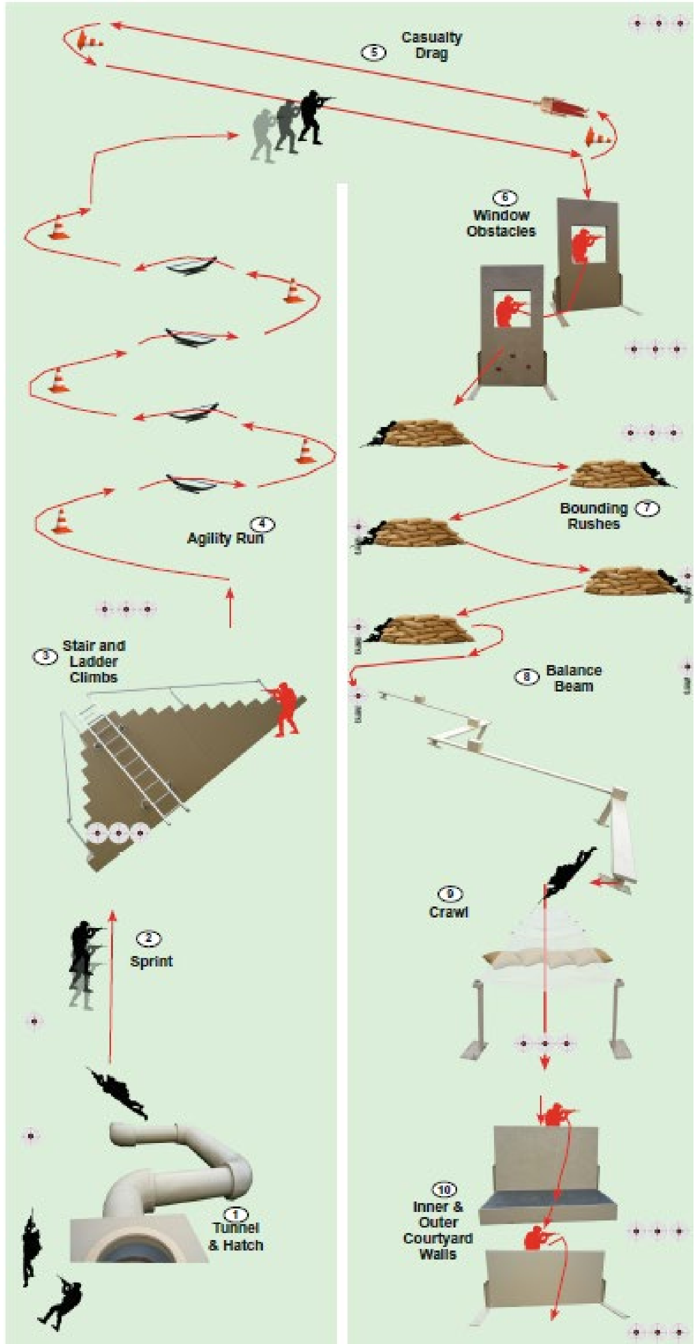


Figure 13: Example of LEAP-MLS course (courtesy of Brown & Mitchell, 2019)

Live Fire Marksmanship

As with simulated marksmanship, live fire marksmanship is another critical performance task when assessing BA system design and impacts on performance. There are pros and cons to live fire testing. For example, it is often difficult to replicate the full recoil and actual noise and feel of shooting a live fire weapon in a simulated weapon scenario. On the other hand, live fire has an innate level of danger associated with it and safety considerations need to be accounted for and can limit the ability to conduct some activities in a training and/or evaluation scenario. Many of the same metrics can be captured from live fire marksmanship as from simulated marksmanship, such as precision, accuracy, probability of hit, probability of lethal hit, aiming time, stability (horizontal, vertical, and overall), trigger control, time between shots, mean target acquisition time, total target acquisition time, engagement time, and total scenario completion time.

Tasks that can be conducted using live fire include a standard qualification test and Soldier-Weapon and Equipment Assessment Tool (SWEAT), an activity being developed by the North Atlantic Treaty Organization (NATO). SWEAT assesses the effects of equipment design on Warfighter mobility and lethality during a live fire task: Soldiers move between firing points as they engage pop-up targets (Figure 15).

The SWEAT course is made up of 11 firing points with 5 physical mobility obstacles (2 walls, 2 windows and an agility run) with prescribed movements between firing points (runs, sprints, crawls, bounding rushes). Mobility obstacles were selected from the LEAP course. Firing points include sandbags, mouseholes, windows, and walls where the Soldier must adopt a prescribed firing posture and scan for, detect, and defeat targets presented within their arcs of fire. There are 29 target engagement scenarios on the course, with one-to-three scenarios at each firing point. 20 scenarios are single-target exposures, while the remaining 9 are dual-target exposures, for a total of 38 targets. More details on the course can be found in Tombu et al., (2023).

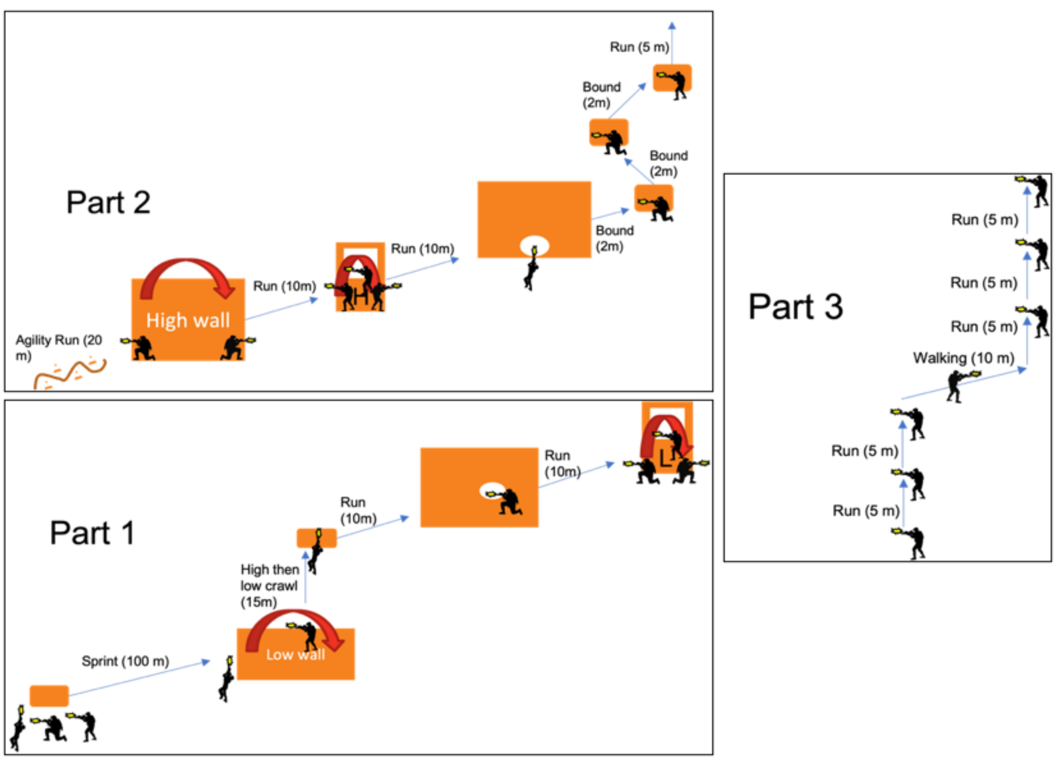


Figure 15: Layout of the SWEAT course (Courtesy of Tombu et al., 2023)

Dismounted Tactical Movements, Road Marches and Wooded Terrain Movements
Dismounted tactical movements encompass road marches, troop movements, and foot patrols. These activities may occur on paved roads or through natural terrain, making real-world hazard assessment possible (e.g., snag hazards in a tightly wooded terrain). They are one of the most common dismounted

tasks and encompass soldiers moving from one point to another on foot (versus via vehicle or aircraft). This task usually includes walking extended distances while carrying all or a subset of the gear needed to complete a mission. The speed of movement varies depending on the abilities of the individuals participating and the mission objectives.

Dismounted tactical movements offer a unique opportunity for testing sustained and easily repeated tasks, for capturing multiple physiological measures (e.g., heart rate, heart rate variability, VO_2 max and consumption levels, muscle activation, etc.), and for overlaying cognitive tasks. The extended timing allows for in-depth quantitative and qualitative BA system comfort and wear assessments like load balance, discomfort points, and BA system feature ease of access. Additional measures may include time to complete movement, speed of movement and/or accuracy of path (via GPS outside a lab environment).

Urban Operations

Urban operations are a common dismounted infantry task that include clearing rooms and securing buildings. Warfighters require situational awareness and the ability to execute a variety of tasks, such as climbing and descending stairs, climbing over and through walls, scanning the environment with the eyes and ears, squatting, taking a knee, and many other full-body mobility tasks. Urban operations require a large degree of dynamic mobility for completing a successful mission.

A simulated military operation in urban terrain (MOUT) can reveal much about a BA system, including mobility, compatibility, and comfort. While newer MOUT sites offer the ability to integrate some objective measures, most times these tasks will be focused primarily on qualitative and subjective information. Efforts are underway to develop more objective measures (e.g., timed specific tasks) and incorporate them into marksmanship tasks to better measure the effects on Warfighter decision making, operational performance, small team/squad level performance, lethality, and survivability.

SUMMARY

This document provides a framework for individuals undertaking evaluations of BA system(s) with respect to form, fit, and function. It highlights numerous considerations that should be addressed prior to undertaking any evaluation of a BA system(s). These include: study goals, participant population, evaluation methodologies, metrics, resources, and safety. This document also highlights critical aspects for capturing participant size and shape via anthropometric measurements prior to participants donning BA systems for any evaluation. The underpinnings of an anthropometric fit assessment are then outlined to determine the optimally sized BA system for a participant so that they can effectively execute any further portions of any evaluation related to the human factors assessment. The document then highlights the critical aspects of human factors analyses, both static and dynamic, to better understand how BA systems can impact movement, mobility, and the ROM of participants.

The methods and tasks outlined in this document are recommendations used and modified by the authors over many years to answer questions related to BA system fit, form, and function. They are not all-encompassing, and the document is intended to be flexible so that new methods and tasks can be added to improve upon any analyses that include the study of BA systems and how they impact fit and size and mobility. The information in this document is critical for the overall design and development of BA systems to understand overall form, fit, and function to improve Warfighter safety and performance.

This document reports research undertaken at the U.S. Army Combat Capabilities Development Command Soldier Center, Natick, MA, and has been assigned No. Natick/TR-24/009 in a series of reports approved for publication.

REFERENCES

Abtew, M. A., Boussu, F., Bruniaux, P., Loghin, C., & Cristian, I. (2020). Enhancing the ballistic performances of 3D warp interlock fabric through internal structure as new material for seamless female soft body armor development. *Applied Sciences*, *10*(14), 4873.

Ashdown, S. P. (2020). Full body 3-D scanners. In *Anthropometry, apparel sizing and design* (pp. 145-168). Woodhead Publishing.

Batty, J.M., Coyne, M.E., DeSimone, L.L., Mitchell, K.B. and Bensel, C.K. (2016). Evaluation of weight effects on a soldier physical readiness test course. *Proceedings of the 2016 American Biomechanics Society*. Raleigh, NC. Aug.

Brewster, F.W. (2014). *Observation Report for the Load Effects Assessment Program – Army (LEAP-A) Pilot Evaluation*. Memorandum 24 December.

Brown, S.A.T., Christopher, J.J., Villa, J.D., Goodenough, R.R., Hancock, C.L., O'Donovan, M. and Mitchell, K.B. (2022). Methodology to assess individual shooting skills that is predictive of squad level performance in a close combat training engagement. *Proceedings of the Human Factors and Ergonomics Society 66th Annual Meeting*. October 2022. Atlanta, GA USA.

Brown S.A.T. and Mitchell K.B. (2019) Preliminary development of an integrated mobility, lethality, and survivability soldier performance testing platform. In: Nunes I. (eds) *Advances in Human Factors and Systems Interaction*. AHFE 2019. Advances in Intelligent Systems and Computing, vol 959. Springer, Cham. Presented at: The 10th International Conference on Applied Human Factors and Ergonomics, July 24-258, 2019, Washington D.C., USA.

Cardello, A.V., Winterhalter, C., & Schutz, H. G. (2003). Predicting the handle and comfort of military clothing fabrics from sensory and instrumental data: development and application of new psychophysical methods. *Textile Research Journal*, 73(3), 221-237.

Choi, H.J., Mitchell, K.B. Garlie, T.N. and DeSimone, L. (2018). Effects of Body Armor Fit on Warfighter Mobility as Measured by Range of Motion (ROM). In *Advances in Physical Ergonomics & Human Factors: Proceedings of the AHFE 2018 International Conference on Physical Ergonomics & Human Factors*, July 21-25, 2018, Loews Sapphire Falls Resort at Universal Studios, Orlando, Florida, USA (Vol. 789, p. 16). Springer. June

Choi, H.J., Mitchell, K.B., Garlie, T., McNamara, J., Hennessy, E. and J. Carson. (2016). Effects of Body Armor Fit on Marksmanship Performance. In *Advances in Physical Ergonomics and Human Factors: Proceedings of the AFHE 2016 International Conference on Physical Ergonomics and Human Factors, Advances in Intelligent Systems and Computing* 489, p.341- 354.

Choi, HJ, Zehner, G.F. & Hudson, J.A. (2009). *A Manual for the Performance of Protective Equipment Fit-Mapping*. Technical report of Research Accomplished, Air Force Research Laboratory, Human Effective Directorate, Biosciences and Protection Division, Biomechanics Branch, Wright-Patterson AFB OH. AFRL-RH-WP-SR-2010-0005. Oct.

Clauser, C.E., Tebbetts, I., Bradtmiller, B., McConville, J.T., & Gordon, C.C. (1988). *Measurer's Handbook: US Army and Marine Corps Anthropometric Surveys, 1987-1988*. (Technical Report (TR-88-043) (AD A202721)). Natick, MA: U.S. Army Natick Research, Development and Engineering Center.

Corlett, E.N., and Bishop, R.P. (1976). A technique for assessing postural discomfort. *Ergonomics*, 19(2).

David, N. V., Gao, X., and Zheng, J. Q. (2009). "Ballistic Resistant Body Armor: Contemporary and Prospective Materials and Related Protection Mechanisms." ASME. *Appl. Mech. Rev*. September 2009; 62(5): 050802. https://doi.org/10.1115/1.3124644. 9 July.

Davis, E.F. (2017). *Executive Summary* – FY2017 Dismounted Soldier Baseline Limited User Assessment Memorandum 28 Apr 2017.

Dutton, B., and Stryker, T. (2016*). FY2016 Dismounted Soldier Baseline Limited Objective Evaluation*. Maneuver Battle Lab, Maneuver Center of Excellence, Columbus, GA.

Dutton, B., and Stryker, T. (2015). *Soldier Load Benchmark Evaluation*. Maneuver Battle Lab, Maneuver Center of Excellence, Columbus, GA.

Garlie, TN & Choi, HJ. (2014). *Characterizing the size of the encumbered Soldier*. Natick Soldier Research, Development and Engineering Center (NSRDEC); Natick, MA. NATICK/TR14/019.

Howard, C.E. (2020). “This vest may save you”: U.S. Body Armor from WWII to Present. *Veritas*. Volume 16, Number 1.

Hotzman J., Gordon, C.C., Bradtmiller, B., Corner, B.D., Mucher, M., Kristensen, S., Paquette,S., & Blackwell, C.L. (2011). *Measurer’s handbook: US Army and Marine Corps anthropometric surveys, 2010-2011*. (Technical Report (Natick/TR-11/017)). Natick, MA.

Kollock, R.O, Hale, D., Vogelpohl, R., Kremer, L., Horner, J., Cox, C., and M. Allen. Then influence of Body Armor on Balance and Movement. *Int J Exerc Sci* 11(1):648-656

Lee, Y. A. (2014). Computer design and digital fit of clothing. In *Anthropometry, Apparel Sizing and Design* (pp. 305-319). Woodhead Publishing.

Lin, YL., Wang, MJ.J. (2016). The development of a clothing fit evaluation system under virtual environment. *Multimed Tools Appl*, 75. 7575–7587. https://doi.org/10.1007/s11042-015-2681-7

Lovell, G and P Evangelista. The effects of body armor load and speed on soldier survivability. USMA *Proceedings of the American Society for Engineering Management 2019 Annual Con*.

Mitchell, K.B. (2017). Encumbered range of motion assessment of a novel body armor system designed to improve mobility. *Journal of Science and Medicine in Sport (JSaMS). Proceedings of the 4th International Congress of Soldier Physical Performance*. November 28-December 2017. Melbourne, Victoria Australia. Nov.

Mitchell, K.B. (2013). *Standard methodology for assessment of range of motion while wearing body armor*. Natick Solider Research, Development, and Engineering Center (NSRDEC). Natick, MA. Technical Report.

Paquette, S.P., Case, H.W., Annis, J.F., Mayfield, T.L., Kristensen, S and, Mountjoy, D.N. (1999). *The effects of multilayered military clothing ensembles on body size: A pilot study*. (Technical Report (TR-99012). Natick, MA: U.S. Army Soldier and Biological Chemical Command, Soldier Systems Center.

Russell, J.D., Delstanche, A., Briston, J., Roberts, A., and Walters, T.E. (in press). *Soldier System Weapon and Equipment Assessment Tool (SWEAT) Pilot Trial*. Defence Science Technology Laboratories (DSTL) TR141291. Porton Down, Salisbury, United Kingdom.

Russell, JD, Delstanche, A, Briston, J, Roberts, A, Walters, TE. (2022). *Soldier System Weapon and Equipment Assessment Tool (SWEAT) Pilot Trial* DSTL/TR141291 v1.0 5 August.

Scharre, P. and Fish, L. (2018). *A Strategy for Enhancing Warfighter Survivability*. Center for a New American Security. https://www.cnas.org/publications/reports/super-soldiers Accessed: 19 January 2023.

Tombu M., Brown, S.A.T., Strick, K., ... & Levin, B. (2023). *Soldier Weapon Equipment Assessment Tool Recommendations*. NATO STO-TR-SAS-145.

Xia, Lei. (2018). *Design and analysis of bio-inspired 3D printing body armor for neck support and protection*. Thesis S.M. in Engineering and Management, MIT, System Design and Management Program.