Designing Military Systems for Women in Combat

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INTRODUCTION

As the role of women in the military expands to include ground combat jobs, it has become increasingly important that the military ensure equipment design considers the physical and cognitive requirements of women so they may operate effectively. Since combat jobs were previously closed to women, equipment used during the conduct of these jobs was not routinely designed with their characteristics in mind. Assessing the extent to which equipment minimizes the risk of Warfighter loss or injury throughout the system development process falls under the purview of the U.S. Army's Human Systems Integration (HSI) Program. It is critical that the HSI community understand female use limitations for equipment currently in the Army inventory and ensure that effective design mitigations and/or training is implemented to overcome any performance or safety issues. It is also critical that females are fully considered during the design of new systems to help prevent adverse health effects as a result of operating the equipment, and to ensure that the equipment itself does not prevent them from performing efficiently. Included in this article are insights gleaned from attempting to account for form, fit, and function in the design of military equipment since we have found that accommodating sex differences is not as straight forward as it would appear. This article highlights some of the challenges faced by the HSI community at-large, recommendations for addressing the challenges, and research needed to better support the materiel acquisition process.

HSI: EARLY, ITERATIVE, WARFIGHTER-CENTERED DESIGN

HSI is the integration of human characteristics into system definition, design, development, and evaluation to optimize human systems performance under operational conditions. The primary goal of HSI is a system design that is more easily trained, operated, and maintained. This is accomplished through scientific research, analysis, and evaluation across seven major Army HSI domains—Manpower, Personnel, Training, Human Factors Engineering (HFE), System Safety, Health Hazards, and Soldier Survivability.[1] Table I contains a definition and sample design question for each of the domains.

The U.S. Army HSI team's strategy initiates HSI efforts as early as possible in the system acquisition process, with the goal of influencing system design to augment cognitive and physical performance, accommodate physical differences, and ensure system designs are useful and usable. This is done best by focusing on intended users and their needs using participatory design techniques and an iterative user-focused design process. Throughout the process, HSI practitioners identify, track, and mitigate human performance issues that threaten total system performance. Issues are corporately maintained in a database maintained by the U.S. Army Research Laboratory, Human Research and Engineering Directorate that enables early data-driven processes leveraging existing HSI data. This restricted access database was searched to identify sex-related design issues involving female Warfighters. More than 50 unique issues were identified in our HSI database related to characteristics of form (a body's shape and size and physical performance characteristics), fit (how well equipment design accommodates the human and facilitates performance of a job/function), and function (demands of a job/task including cognitive and physical workload, fatigue, and environmental factors such as temperature, humidity, lighting noise and vibration). Table II contains a list of the top five sex-related HSI issues identified in the database, which account for 84% of those observed from 1953 through 2014. Also included in the table is the frequency of their occurrence and an example of their potential operational significance. In some cases, issues have been resolved (e.g., torque was reduced on the main rotor blade retention bolts) and in other cases, the issue has become the focus of research (e.g., seating in aviation and ground tactical vehicles). As shown in the Table II, issues may fall into multiple HSI domains.

The operational user needs statements codified in requirements documents determine physical and task standards that drive physical and task performance requirements, which in turn drive equipment design. However, if operational user needs statements are not fully understood from the human point of view and integrated into research, design, and systems engineering at the onset of the requirements generation processes, the equipment design—software and hardware—will fail the human. This failure is not trivial. It may result in fratricide (friendly fire),[2] increased acquisition costs,[3] and physical designs that exclude smaller and larger men and women from operating and maintaining equipment.[4] Preventing these failures requires consideration of the human, male and female alike, as an integral component in design through the application of HSI tools, techniques, and methodologies.

The remainder of this article draws from design literature, research, and lessons learned to provide examples of how

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TABLE I. HSI Domain Definitions and Sample Design Questions

HSI Domain	Definition	Sample Design Question
Manpower	The numbers of military and civilian personnel required and available to operate, maintain, sustain, and provide training for a system.	Will manpower requirements increase if women maintain equipment?
Personnel	The cognitive and physical capabilities required to be able to learn to operate, maintain, and sustain a system.	Are there gender differences that impact equipment design and operational readiness?
Training	The instruction or education and on-the-job or unit training required to provide personnel with the essential job skills, knowledge, and attitudes to effectively use a system to accomplish their goals.	Is there gender-specific information that must be conveyed during training?
HFE	The integration of human characteristics into system definition, design, development, and evaluation to optimize human–machine performance under operational conditions.	Has the anatomy of the female Soldier been adequately considered during design to assure operability and maintainability of equipment?
System Safety	The design features and operating characteristics of a system that serve to minimize the potential for human or machine errors or failure that causes injurious accidents.	Has exposure to workplace risks accounted for the presence of gender differences?
Health Hazards	Consideration in the design features and operating characteristics of a system that create significant risks of bodily injury or death; prominent sources of health hazards include acoustics energy, chemical substances, biological substances, temperature extremes, radiation energy, oxygen deficiency, shock (not electrical), trauma, and vibration.	Have design features that create significant risks to bodily injury accounted for the presence of gender differences?
Soldier Survivability	The characteristics of a system that can reduce fratricide, detectability, and probability of being attacked and minimize system damage, soldier injury, and fatigue (both cognitive and physical).	Have cognitive and physical fatigue gender differences, if any, been accounted for in design?

the U.S. Army is assessing current designs and addressing unique sex-related characteristics to better accommodate female Warfighters.

ACCOMMODATING THE FEMALE PHYSIQUE

The inability to physically reach controls and equipment was the most commonly occurring design-related issue affecting operational performance of females identified in our historical HSI database. The next most frequently occurring issue involved lifting and carrying weights that exceeded mixed-sex limits for a variety of equipment including transit cases, generators, and weapon system components. As documented by HSI practitioners, exceeding these limits increases risk of musculoskeletal injury, injury from falling objects, and slower mission execution. Feuerstein et al[5] analyzed 41,750 disability cases and found that certain occupations were associated

TABLE II. High-Frequency Issues Present in the 1953 to 2014 U.S. Army Research Laboratory, Human Research and Engineering Directorate HSI Issues Database

Frequency of Occurrence *N* (%)	HSI Domain	Issue	Example and Operational Significance
20 (27%)	HFE	Inability to physically reach controls and equipment.	Smaller female aviators were unable to fully reach brake pedals and the front instrument panel. Restricted physical access to flight controls will prevent smaller female soldiers from effectively operating aircraft.
12 (18%)	Manpower and System Safety	Lifting weights exceed mixed-gender limitations.	An increase in manpower (to 2 personnel) is required when 1 member is female.
13 (18%)	System Safety	Carrying weights exceed mixed-gender limitations.	Commanders must compensate for slower movement when planning missions.
9 (12%)	HFE and System Safety	Seating (including footrests, backrests, and armrests) does not accommodate female soldiers in the lower height percentiles.	Awkward postures will cause discomfort and increase the risk of fatigue which can negatively impact soldier performance.
5 (7%)	HFE and System Safety	Inability to exert force required to engage or move an object.	Potential saving of 0.33 man-hours could be achieved if the force required to break torque on the main rotor blade retention bolts were reduced so a fifth percentile female soldier could safely and easily accomplish the task.

with greater risk for musculoskeletal injury and that women experienced higher rates of musculoskeletal disabilities when compared to men. The five occupations with the highest risk to females, which also pose greater risk to women when compared to men, were: multichannel transmission systems operator, single-channel radio operator, wheeled-vehicle mechanic, signal intelligence analyst, and voice interceptor.[5] Using the same database, Berkowitz et al[6] found very similar results when identifying occupational disability differences between men and women with higher rates of injury for female unit level, wheeled-vehicle mechanics; single-channel radio operators; multichannel transmission systems operators; interrogators/translators; and practical nurses. These jobs involve awkward postures, are physically demanding, and involve lifting and carrying heavy equipment.[7]

Designing equipment to help reduce risk of injury can be challenging as the maximum design weight limits are reduced by nearly 50% when designing for mixed sex as compared to male only designs in accordance with Table XXXVIII in Military Standard 1472.[8] These operational issues are being addressed through research and advances in science and technology (S&T) that are enabling the design of lighter weight materials to reduce the physical burden placed on male and female Warfighters alike.[9] Another area of S&T research that has been in development for decades,[10] seeks to augment physical performance by increasing Warfighters' physical strength and endurance through mechanical augmentation using exoskeletons.[9] As the military transitions exoskeletons from the laboratory to the field, HSI practioners work to influence their design to maximize their usability in military missions.

Another common issue identified in our HSI database involves the strength required to operate equipment exceeding that of the fifth percentile female. Here, examples include the strength required to set parking brakes for vehicles on severe slopes, breaking torque on retention bolts, and pulling release levers. Risks associated with these issues include damage to equipment, injury to vehicle occupants, and musculoskeletal injury that threaten operational and unit readiness. Accommodation issues included the inability to adequately adjust seats fore/aft/up/down which in turn, limited field of view and lines of sight, increased difficulty reaching controls and viewing displays, induced awkward postures, and interfered with ability to view exterior terrain from a popped hatch seated position. Preventing future occurrence of these issues is possible by considering the female physique during early analysis and workspace design, creating innovative design solutions that focus on accommodation, and continuing to transition S&T advancements to the acquisition community.

One of the primary goals for workspace design is to optimize accommodation of intended users, which in turn helps to maximize productivity and performance and minimize strain, fatigue or other occupational risk factors leading to injury. Designers strive to achieve a balance between the anthropometry of the target user population, operator tasks, and the physical size and layout of the workspace components.[4,11] This is especially true for military ground and aviation platforms, where most systems seek to achieve, at a minimum, a central 90% accommodation goal of the combined male and female target user population. In many instances, the anthropometric extremes of the target population are used to establish workspace design parameters. Because of the significant gap in most physical dimensions between men and women, small female and large male body sizes typically define the boundary ranges for the accommodation envelope.[12] Although the univariate approach of using 5th percentile female to 95th percentile male key body dimensions have been traditionally used to define a desired accommodation target, it usually results in a design that actually accommodates less of the population than the percentile range would imply.[13]

A more effective approach for defining an accommodation range is through the use of a multivariate statistical method such as Principal Component Analysis that incorporates a set of critical body dimensions intrinsic to the system design. It allows a desired range of a population to be accommodated in such a way that the size differences as well as body proportion variability are taken into account. A set number of manikins or forms that define the boundary or range of the desired population accommodation can be represented using 3-dimensional human figure modeling tools as shown in Figure 1.

Also, models of mission essential clothing and equipment can be added to assess actual encumbered conditions shown in Figure 2.

The use of human figure models can help to assess and quantify component adjustment ranges needed early in the design process for males and females alike. Anthropometrically and biomechanically accurate human figure models or body manikins can be used to visualize the geometric relationship between the human body and equipment design. Reach

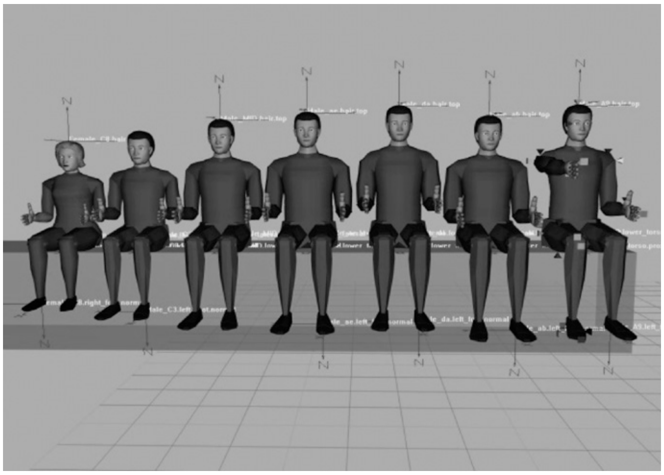

FIGURE 1. An example boundary manikin set illustrating various human figure model types (from left to right): small female, small male, mid-sized male, wide torso male, long torso male, long limb male, and large male.

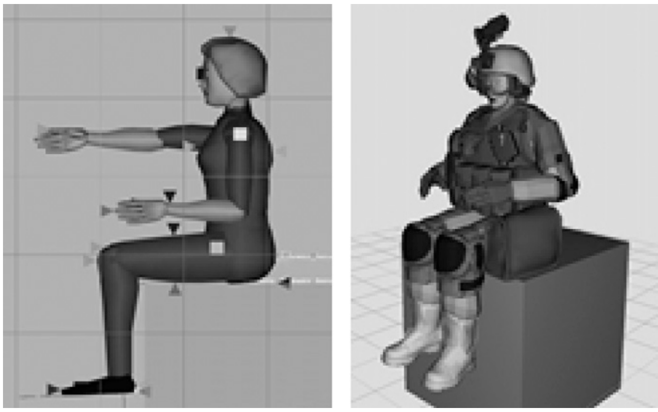

FIGURE 2. Small female manikin (left), with added clothing and equipment models (right).

restrictions to operational controls or the ability to perform a maintenance task within a confined space can be quickly assessed in relation to critical body dimensions of the target user population. Models of mission essential clothing and equipment can be added to the manikins to assess actual encumbered conditions (Fig. 2). The inability to accommodate females when encumbered—wearing mission-oriented protective posture gear (used to protect Warfighters when exposed to toxins in a chemical, biological, radiological, or nuclear strike) as well as other mission-essential gear—is another issue present in our HSI database. The presence of this issue and the need to mitigate it provides further evidence of the importance and benefits derived from using human figure modeling to evaluate the effectiveness and suitability of materiel solutions. Furthermore, these manikin sets can be integrated into the computer-aided design model of the system design to help identify shortcomings early in the design process when recommended design changes are easier and less costly to implement.

ACCOMMODATING COGNITIVE CONSIDERATIONS

Thus far we have discussed real differences—physical differences—between men and women and have provided highlights of how these differences can be accommodated through design. But, are there other differences—cognitive differences or physical differences affecting cognitive abilities—which we should also be addressing through training and system design?

Two initial topics were identified—navigational strategies to find a target location and the propensity to experience motion sickness since both could conceivably affect an individual's ability to accomplish cognitively demanding mission activities. Our intent was to identify sex-related differences that decrement performance in order to understand where to place design and training emphasis during future system development efforts.

Decades of research has focused on spatial differences between the sexes. In general, males tend to exhibit better spatial abilities than females[14] and since navigation is largely based on spatial abilities, it is reasonable to expect males to outperform females in navigation tasks. However, research results are mixed. Some studies support the expectation that males are better,[15] some do not,[16] some find mixed results,[17–19] and still others fail to reveal any significant differences.[20–22] These varied results are attributable to the manner in which the navigational task is presented, the instructions provided, and the stimuli used all of which may be tapping different underlying cognitive abilities. For example, Tlauka et al[15] examined navigation using two large-scale virtual shopping centers in which subjects received either a handheld paper map or a digital map displayed on a computer screen to assist in completing a battery of tasks that included wayfinding and assessing directional and distance estimates. They concluded that virtual exploration like real-world learning, leads to differences in spatial performance in which males outperform females. Porathe[20] had subjects drive a small vehicle (0.45 m by 0.38 m) that simulated a boat navigating through water through four different mazes (6 m by 6 m) using a traditional paper map, an electronic map in north-up mode, an electronic map in course-up mode, and a 3D map. Nonsignificant results for sex were found for the time spent on track and the number of time in which the "boat" ran aground. Andre et al[22] tested participants using a map with road grids and a compass that was oriented as north-up and one that was orthogonal to the map's grid. Subjects were instructed to find a route on a map and provide directions for it. Results were analyzed to determine if there were sex differences in the number of times that cardinal terms (north, south, etc.) and directional terms (left, right, etc.) were used. No significant sex differences were discovered. However, these examples serve to demonstrate some of the research variability present in sex studies of navigational ability and the challenge designers face translating results to actionable information for design; this is what interests us the most—how to apply the findings to system design. Several researchers have proposed some promising design considerations to address potential sex issues.[23–26] For example, Hubona et al[23] propose that a "sex neutral" interface design can be accomplished by decreasing user reliance on spatial abilities through the addition of meaningful landmarks and by converting spatial information to textual content. Waters et al[24] propose improving training and navigation through the development of wayfinding aids. Tan et al[25] suggest using larger displays with wider fields of view to provide better optical flow cues to improve 3D virtual navigation. Finally, Feng et al[26] purport that playing an action video game for 10 hours can eliminate sex differences in spatial attention and decrease differences in mental rotation ability. These are all viable candidates for consideration in future navigational system design.

Research often states that women are much more prone to motion sickness than men,[27,28] but other studies show that when men and women are grouped according to their self-reported high or low susceptibility to motion sickness, analysis of simulator sickness questionnaire responses finds no significant sex differences.[29–31] Rather than relying on retrospective survey questionnaires and self-reporting, Cheung et al[32] used physiological measures of motion sickness—calf blood flow, blood pressures, and heart rate, which have been demonstrated to be reliable physiological measures,[32–34] when exposing subjects to Coriolis cross-coupling stimulation (rotating platform that produces the illusion of rolling and yawing in opposite directions and induces symptoms of motion sickness).[31] Although no physiological responses indicated the presence of motion sickness differences between the sexes, females were more inclined to admit discomfort than were males. Applied research investigating the usability of command and control systems in moving tactical ground vehicles has found that motion sickness decrements performance.[35] Not only did study participants become nauseous and vomit one became unconscious and required medical evacuation.[35] Although little is known about the underlying physiological mechanisms contributing to motion sickness,[36] clearly we must obtain a better understanding in order to compensate for its debilitating effects when Warfighters must perform cognitively intense tasks while operating equipment on-the-move.

IMPLICATIONS FOR FUTURE RESEARCH AND THE MATERIEL ACQUISITION PROCESS

Military materiel solutions have not historically or systematically considered the female Warfighter as an operator and maintainer throughout the acquisition process since not all positions were open to them. As positions continue to become open to females, it is critical that their physical characteristics (e.g., physique, strength) be considered during research as well as during the design and development of new materiel solutions that are being procured by the military, or design attributes will have the potential to induce injury and suboptimal performance. It is also recommended that risk assessments of existing equipment in the military inventory be conducted to identify current risks and their magnitude to female service members as well as effective mitigations or precautions to prevent harm and suboptimal performance. Mitigations may be achieved through materiel as well as nonmateriel changes. For example, a nonmateriel solution could involve changing tactics, techniques, and procedures such as increasing manpower when tasks involve carrying equipment with weights that exceed mixed-sex limitations, whereas a materiel solution could involve use of an exoskeleton to offload the weight from its wearer. In addition, military standards must be updated to include design limits for all female crews, since standards only exist for male-only and mixed crews. Materiel requirements must specify female physical requirements stated as anthropometric measures, strength, and weight factors to ensure equality of design for all Warfighters across the Joint Services.

Research investigating the cause of poor navigational abilities and motion sickness do not consistently identify the presence of sex differences; however, these are critical factors that affect a Warfighter's ability to perform mission essential tasks. This leads us to believe there is still a great deal that needs to done to more fully understand these phenomena and how best to mitigate their detrimental performance effects through effective system design.

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