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An Integrated Human Figure Modeling Analysis Approach for the Army's Future Combat Systems

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ABSTRACT

A prime concern for the U.S. Army's Future Combat System (FCS) is ensuring that human system integration requirements are met. To that end, an integrated human figure modeling approach has been developed to help meet those goals. The accuracy of any analysis that uses human figure modeling tools depends not only on the data and method used to construct the figures but also on the clothing and equipment items worn or transported by the operator or vehicle occupant. Some of the keys to this approach incorporate methods for estimating the physical size of the user population as well as defining the Soldier clothing and equipment for the 2015 time frame when the FCS is scheduled to be fielded. The four primary areas of focus for analyses include the common crewstation, squad area, egress/ingress, and maintenance. The cooperative approach has been devised by the U.S. Army Research Laboratory, the U.S. Army Natick Soldier Center, Boeing (FCS lead system integrator), and platform developers (United Defense and General Dynamics Land Systems).

INTRODUCTION

The U.S. Army is developing Future Combat Systems (FCS) to provide the capability to rapidly project a dominant ground force anywhere around the world within days. At the time that the integrated human figure modeling approach discussed in this paper was developed, FCS was expected to be fielded in 2015. The FCS manned ground vehicle plan calls for a family of approximately 15 different combat vehicles based on a common platform. Each vehicle will be distinct when equipped and assembled with a unique mission module system consisting of a combination of carrier and/or ordnance systems. The FCS common platform will be compatible with transporting and fielding in a combat-ready configuration on a C-130 military air transport. To realize the benefit of rapid deployablity in a C-130, FCS vehicles must meet size and weight constraints that make it critical that estimation of the space necessary to accommodate the operators and maintainers of these vehicles is efficient and accurate. The acquisition approach to designing these platforms involves a lead systems integrator (LSI), Boeing, overseeing design efforts by vehicle developers, United Defense and General Dynamics with Government participation in geographically dispersed integrated product teams. This acquisition approach as well as the size and complexity of the development effort make it critical that a common analytical approach be used. In previous Army acquisition programs, differences in data, analytical tools, and methodology led to difficulty in timely, accurate, and decisive evaluation of vehicles. The common human figure modeling analysis approach for FCS addresses these concerns.

APPROACH

OVERVIEW

The goal of the integrated approach is to provide all the data and guidance necessary to make FCS operator and maintainer accommodation design decisions but eliminate sources of disagreement concerning validity or ability to compare results across the FCS team (LSI, Government, and platform developers). Fortunately, the human factors engineers on the FCS team agreed that the goal was important and that team members would follow the approach.

To achieve the goal, sources of variability among team member approaches were considered:

1. Source of the anthropometric (body measurement) data used to perform accommodation analyses (i.e., which survey, database, or standard).

2. Projection of anthropometric data to fielding date of the system to include accounting for secular and demographic trends.

3. Statistical method of sampling anthropometric data for sizing manikins and testing for accommodation (univariate versus multivariate).

4. Procedure for sizing human figure model manikins against anthropometric data.

5. Method for considering clothing and equipment worn and used by operators and maintainers.

6. Human figure modeling software used to perform analyses (i.e., software package).

7. Sources, currency, and format of computer-aided design (CAD) files representing the vehicle designs.

8. Techniques for using human figure models to evaluate accommodation, considering factors such as positioning manikins and specific types of accommodation (e.g., reaching, line of sight, head clearance).

The resulting approach attempts to address these sources of variability. The basic steps of the FCS human figure modeling analysis approach are

1. Derive a common set of anthropometric data for use in analyses:

a. Determine key accommodation analyses for FCS vehicles and the critical anthropometric dimensions associated with those analyses;

b. Project anthropometric data from the most recent, 1988, Army anthropometric survey (ANSUR 88) to the year 2015 for each of the critical dimensions;

c. Derive dimensions to use in sizing manikins using multivariate rather than univariate statistics.

2. Build clothed and equipped human figure model manikins from the anthropometric data:

a. Build boundary manikin sets in human figure modeling tools;

b. Add digitized clothing and equipment;

c. Validate the combined manikin and clothing model against 3-D scan data;

d. Distribute manikins to FCS team.

3. Obtain CAD files of vehicles and optimize for use with human figure modeling tools.

4. Perform analysis:

a. Place manikins in CAD file;

b. Check for static and dynamic accommodation;

c. Develop recommendations for addressing accommodation issues identified.

The sections of this report that follow detail the steps of the human figure modeling analysis approach.

ANTHROPOMETRIC DATA

Key Accommodation Analyses

The FCS team determined that four analytical categories would likely be necessary for FCS vehicles:

- Crewstation design (can the Soldier reach and see all the controls and displays?),
- Ingress and egress (can the Soldier enter and leave crewstations and the vehicle?),
- Troop compartment seating (can infantry with all their equipment sit comfortably in troop-carrying vehicles?), and
- Maintenance (can crew and mechanics access, remove, and replace parts?).

Then, candidate critical anthropometric dimensions were determined for each of these analyses. For example, 11 measurements (sitting height, knee height – sitting, buttock knee length, functional reach, chest depth, buttock popliteal length, biacromial breadth, bideltoid breadth, popliteal height – sitting, eye height – sitting, and acromion height – sitting) were considered as critical dimensions for crewstation analysis. These dimensions were used in the derivation of the multivariate accommodation envelopes described next.

Anthropometric Database Selection and Preparation

The most recent anthropometric survey of Army personnel was conducted in 1988 (ANSUR). Other data sources are less relevant for Army application. For example, the Civilian American and European Surface Anthropometry Resource (CAESAR) project surveyed civilians, many of them not from the United States. The 1988 ANSUR included oversampling of demographic minority groups so that statistical weighting of subjects could be used to adjust for expected shifts in Army demographic composition (Gordon et al., 1989; Gordon, 1997; Gordon, 2000). Because the database as a whole (n=5077 males, n=3458 females) is oversampled, it is not representative of any population. Before anthropometric analyses of the ANSUR database are conducted, subjects in the database must be randomly sampled with demographic subgroup probabilities matching prevailing Army age/sex/race distributions (as in Gordon et al, 1989) or individual subjects in the database must be weighted to match prevailing demographic distributions (as in Gordon et al, 1997). Census data for Army populations are compiled on a quarterly basis by the Defense Manpower Data Center (2002), and these form the basis for generating sampling fractions that ensure analyses are based on demographic distributions representative of the Army.

If we assume fielding in the year 2015, secular trends (change over time) in the body size of American populations between 1988 and 2015 must be accounted for in the anthropometric estimates. Because rates of secular change for various body dimensions differ among American subpopulations (Greiner & Gordon, 1990, 1992), incorporation of secular changes into engineering design criteria requires two steps: 1) estimation of Army demographic composition in the year 2015 to obtain database subject weights that match 2015 Army age/sex/race distributions, and 2) adjustment of body measurements to reflect the secular increases or decreases in body measurements expected between 1988, when ANSUR subjects were measured, and 2015, the Army population we want to represent.

American census research provides insight into the demographic composition of present and future American populations, and Army census, retention, and recruiting data provide insights into the present and near-term demography of the Army. However, prediction of Army demography a decade or more in the future depends heavily on knowledge of demographic trends in American populations and on knowledge of demographic variation in both military eligibility and volunteerism (Gordon & Greiner, 1993). To date, no comprehensive predictive model has been developed that incorporates American census projections and those factors that make Army demographics different from the American civilian population, including differential rates of eligibility and differential rates of volunteerism and retention (Maxfield, 2003; Watrous, 2003). In the absence of specific demographic projections of future Army populations, statistical analyses in this project assumed no demographic change between 2002 and 2015 and used subject weights calculated from active duty Army demographic distributions as of 30 October 2002, received from the Defense Manpower Data Center (DMDC, 2002).

Trends of secular change in the body dimensions of Soldiers have been studied extensively (Greiner & Gordon, 1990, 1992, 1993) with cross-sectional data from major Army anthropometric surveys such as those conducted in 1918, 1946, 1966, 1977, and 1988. However, to accurately derive secular trend models from anthropometric surveys, the body dimensions in question must have been measured comparably in every survey or else changes in body size over time will be confounded by variation in measurement definitions and techniques among surveys. For this reason, independently derived secular trend models are available for far fewer body dimensions than are required for specification of digital human models.

To provide secular trend adjustments for the 50 or more body dimensions required for digital man models, sex and race-specific multiple regression equations using height and weight to predict other body dimensions were used. This approach is a variation of the proportional scaling method described by Pheasant (1996). In this case, however, we used race-specific regression equations and secular change models because body proportions and rates of secular change are known to differ significantly among Army demographic groups (Greiner & Gordon 1990, 1992, 1993; Gordon & Greiner, 1993). In addition, predictive accuracy and stability depend on our having good sample sizes of the subgroup in question in several major surveys distributed over a long period of time. However, Army populations have only recently included significant numbers of demographic minority groups such as women, Native Americans, Asian Americans, and Pacific Islanders. As a result, available secular trend models for these demographic minority groups are substantially less reliable than those for White, Black, and Hispanic male subgroups (Greiner & Gordon, 1990, 1993), which together comprised 79.4% of the active duty Army in 2002. As a result, it was decided that for this study, secular adjustments would be made only in those demographic groups with well-defined secular trend models.

Derivation of Multivariate Accommodation Envelopes

Body dimension specifications for digital man models on the periphery of male and female 90% accommodation envelopes were derived with multivariate statistical methods because crewstation display and control locations and seat adjustment mechanisms must accommodate many critical body dimensions simultaneously for the operator to use the crewstation effectively. When simultaneous accommodation of multiple body dimensions (e.g., sitting height, leg segment lengths, and arm segment lengths) is required, univariate percentile ranges cannot be used to establish design and testing criteria for several reasons. Body dimensions are not perfectly correlated with one another, so different people may be outside the 5th to 95th percentile ranges for different variables which results in a simultaneous accommodation rate far below the intended 90% (Moroney & Smith, 1972). Uniformly large and uniformly small models such as those described by 5th to 95th percentile boundaries do not necessarily describe the engineer's worst case scenario, namely, combinations of extremely large and extremely small values in the same subject which may be critical to design (Roebuck et al., 1975; Bittner et al., 1987; Hendy, 1990; Zehner et al., 1992). Finally, because percentiles are not additive, human models created from percentile segments are unrealistic in both size and shape (Churchill, 1978; Robinette & McConville, 1981; Annis & McConville, 1990).

To validly describe extremes of both body size and shape in user populations, multivariate statistical analyses such as Principal Components Analyses (PCA) have been used (e.g., Bittner et al., 1987; Zehner et al., 1992; Gordon et al., 1997; Gordon, 2002). PCA reduces the dimensionality of the accommodation envelope from *n*-space (where *n* is the number of body dimensions that are critical for design accommodation) to a smaller

number of dimensions (e.g., 2 or 3) that account for a large proportion of the original variation by using linear combinations of the original measurements. Further, PCA identifies important "large-small" body dimension combinations when they are important in the covariance structure, and the method generally creates one or more principal components that actually measure such extremes of shape. After derivation of the principal components, database subjects can be scored and plotted in the new PCA space, and a two- or three-dimensional (3-D) ellipse or ellipsoid can be fit to the population distribution in order to capture whatever percentage of users is desired.

Table 1 illustrates a PCA of male Soldiers conducted on the correlation matrix of seven critical crewstation design variables: acromion height seated, biacromial breadth, buttock-knee length, eye height seated, popliteal height, sitting height, and thumbtip reach. As described earlier, subjects were weighted to match 2002 Army age and race distributions, and with the exception of Native Americans and Asian/Pacific Islanders (for whom secular trend models are unstable), the measurements of all subjects were projected to the year 2015. As can be seen next, the first three principal components (PCs) together account for 91% of the variation present in the original seven variables. PC1, which captures 59.4% of the original variation, describes overall body size: the largest values of PC1 occur when all body dimensions are large. PC2, which accounts for an additional 21.7% of the original variation, contrasts limb lengths with torso height: the largest values of PC2 occur when a Soldier has long limbs and a short torso. PC3, which accounts for an additional 9.9% of the original variation, primarily describes variation in shoulder breadth and contrasts it with arm/leg lengths and shoulder height. The largest values of PC3 occur when a Soldier has broad shoulders and a relatively short trunk and limbs.

Table 1. Principal Component Analysis of Army males

Male PCA7 (n=5077)

Component	Eigenvalue	Difference	Proportion	Cumulative
1	4.15553	2.63386	0.5936	0.5936
2	1.52167	0.83027	0.2174	0.8110
3	0.69141	0.43125	0.0988	0.9098
4	0.26016	0.05107	0.0372	0.9470
5	0.20909	0.06813	0.0299	0.9768
6	0.14096	0.11979	0.0201	0.9970
7	0.02118	.	0.0030	1.0000

	Eigenvectors		
Variable	1	2	3
ACRHTST	0.38654	-0.41061	-0.17926
BCRMBDTH	0.29455	0.17424	0.92279
BUTTKLTH	0.37039	0.40612	-0.15846
EYEHTSIT	0.41363	-0.40743	0.0165
POPHGHT	0.37699	0.36758	-0.25946
SITTHGHT	0.41514	-0.40534	0.01139
THMBTPR	0.37562	0.41315	-0.15326

A PCA was conducted separately on U.S. Army females to avoid the biases incurred by force-fitting a multivariate normal model over sexually dimorphic (essentially bimodal) distributions (Gordon et al., 1997). The results are similar to those of the male subjects in that the first three PCs have similar interpretations and explain similar amounts of variation in the original data.

Once the PCA is completed, database subjects are scored on the new composite variables (PCs), which now describe the most important components of variation in both size and shape. Subject PC scores are plotted in 3-D PC space and an ellipsoid capturing a specified percentage of subjects is fit to their distribution. The surface of the ellipsoid represents the accommodation envelope associated with the percentage of subjects chosen. Twenty-six boundary forms on the surface of the ellipsoid at major axis intersections and midpoints between intersections can then be used to represent extremes of both size and shape present in a certain percentage of users for the original *n* body dimensions considered simultaneously. They are, in essence, a family of worst case engineering scenarios at the limits of a specified accommodation envelope. The central form, situated at the intersection of the three PC axes, represents a multivariate "average" body form.

BUILDING MANIKIN SETS

After the anthropometric data for building the boundary manikin sets have been derived, it may seem that all that is required to produce the digital human models is to enter data into a human figure modeling package such as Jack[1] or Safework Pro[2] and wait for the software to automatically produce the individual models that comprise the set. While many human figure modeling packages do have the ability to generate default or "library" figures at the click of a button, the creation of custom figures usually involves more effort. The procedure outlined next covers the method for generating these custom boundary figures using Jack v4.0 software.

[1]Jack™ is a registered trademark of UGS
[2]Safework® Pro™ is a registered trademark of SAFEWORK, Inc.

The Jack software includes an advanced body scaling utility. This interface (figure 1) features input for 26 specific body dimensions that can be used to build custom sized figures. In addition to the advanced scaling utility, a body part scaling interface is also provided. This interface allows the user to scale individual body segments of the human figure.

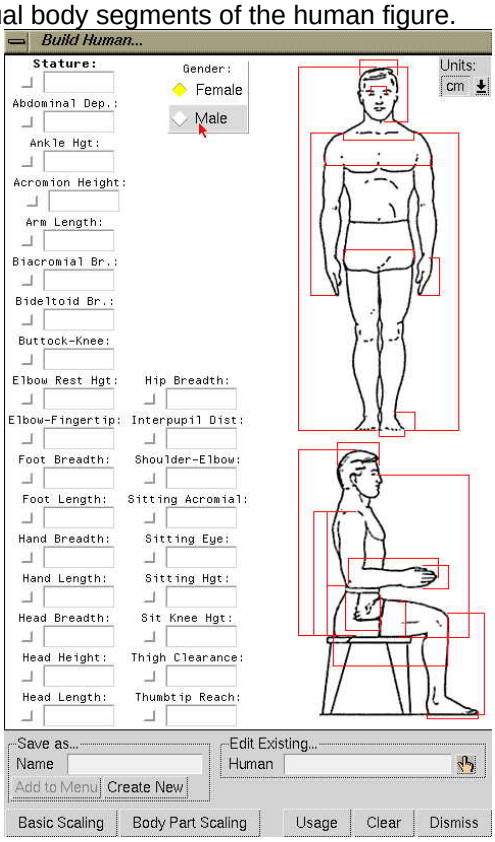

Figure 1. Jack v4.0 advanced figure scaling interface.

Each anthropometric datasheet for building the individual figures in the boundary manikin set supplies 55 body dimensions. The figures in the FCS boundary manikin can be built to match the anthropometric datasheet body dimensions to a tolerance of 2 mm by using a combination of the advanced scaling and the body segment interfaces.

However, the scaling process is not as easy as entering numbers into the interface. Some of the dimensions are cumulative. For instance, sitting height includes sitting eye height, acromial sitting height, and elbow height. If one dimension is changed, the program may change the other dimensions by some proportion that was unintended. A constant process of rechecking all changes is required to achieve the desired result. For example, if the figure's seated height dimension is changed, the seated acromial height and the seated eye height dimensions will also change unless these dimensions have been locked. Likewise, if the bideltoid breadth dimension is changed, the chest breadth and biacromial breadth will also change unless these dimensions have been locked. Throughout this construction process, a series of reference markers can be used to pinpoint the exterior body landmarks that represent anthropometric measurement points on the Jack figure model. These markers should be stored with the reference figure model as a visual check against unintentional changes in dimensions that should remain fixed (figure 2). When each figure is completed, a final point-to-point measurement of all critical figure dimensions should be performed to ensure the highest degree of accuracy.

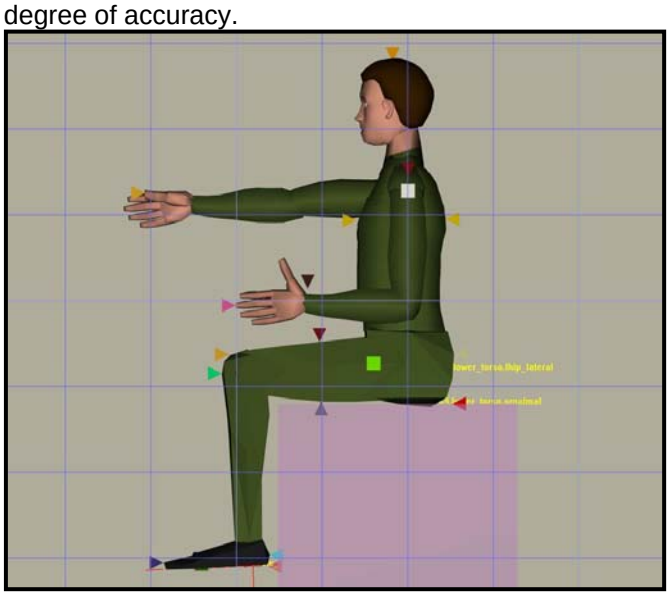

Figure 2. Large male figure with file reference markers

A subset of seven figures from the FCS crewstation boundary manikin set is shown in figure 3. The figure illustrates the variation in the body dimension proportions from within that set. These figures depict the population extremes with the small female and large male, as well as some of the widest variations in limb and torso dimensions.

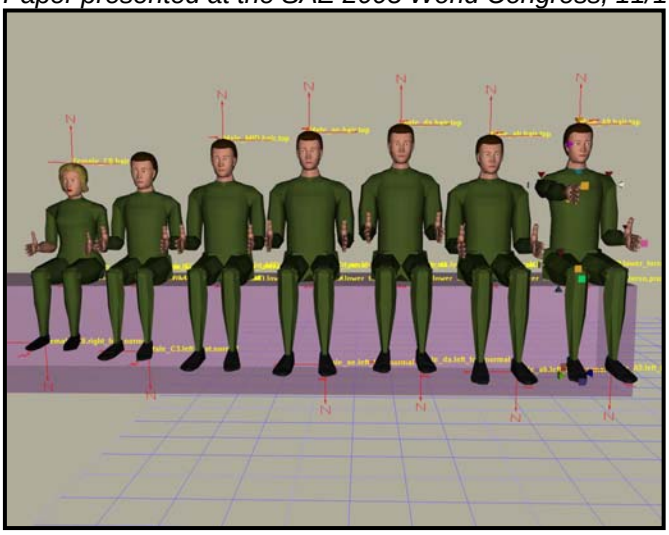

Figure 3. Selection of several boundary manikins from the FCS crewstation manikin set.

DEVELOPING 3-D CLOTHING AND EQUIPMENT MODELS

Typically, analyses with human figure modeling are performed with unclothed body models. While the reasons for performing the analysis in this manner vary, the reason is frequently because the desired clothing and equipment models are non-existent. The task of accurately creating a set of human figure models to perform an analysis is challenging. When clothing and equipment models are added to the mix, a whole new layer of complexity is encountered. However, specialized clothing and equipment may have a severe impact on a person's range of motion, field of view (FOV) and ability to fit in a workspace, thus making it difficult for the person to complete required tasks successfully. For this reason, efforts using human figure models to analyze these workplaces and associated tasks should also include models of the same specialized clothing and equipment (Kozycki, 1998; Kozycki & Gordon, 2002).

To assess FCS designs properly, it is critical to develop models of the clothing and equipment items that will be in use at the time the FCS is fielded. FCS requirements state that the vehicles must accommodate the target Soldier population plus all mission-essential clothing and gear. To address this issue, the U.S. Army Research Laboratory has begun building a library of clothing and equipment models optimized for human figure modeling analysis. These models are sufficiently detailed to accurately represent the surface and bulk of items while minimizing polygon count and file size for human figure modeling use. Programs such as Land Warrior (LW) and Future Force Warrior (FFW) are two such Army initiatives that are developing the concepts for future individual Soldier clothing and equipment ensembles. As prototypes of these concepts become available, they are digitized and added to the library. Figure 4 shows several human figure models in various postures with FFW build I clothing and equipment. Currently, the ARL digital library includes models of several dismounted Soldier items such as packs, helmets, boots, battle dress uniform (BDU) trousers and shirts, as well as several weapons and vehicles.

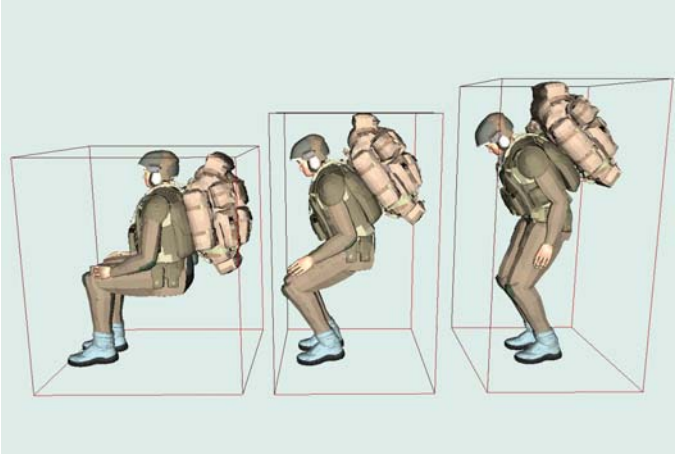

Figure 4. Human figure models in various postures wearing the digitized FFW build I clothing and equipment. (The surrounding boxes represent the associated space claims for each posture.)

The use of the four boundary manikin sets developed for FCS without the proper digitized clothing and equipment models could lead to designs that would otherwise be insufficient in providing vehicle space necessary to accommodate the target Soldier population. However, to properly use these manikin sets, care must be exercised so that clothing and equipment items are digitized accurately and fitted correctly on the figures. The U.S. Army Natick Soldier Center (NSC) will play a key role providing the FFW clothing and equipment items for digitizing. The NSC will also use a whole-body scanner to validate the accuracy of the clothed human figure models by comparing 3-D scans (figure 5) to the human figure models with the same digitized clothing and equipment ensembles.

There are two benefits to digitizing these future clothing and equipment concepts. Not only can these models help to predict the true space claim requirements for FCS, but they can be used to help tailor LW and FFW concepts to fit within limited FCS space claims.

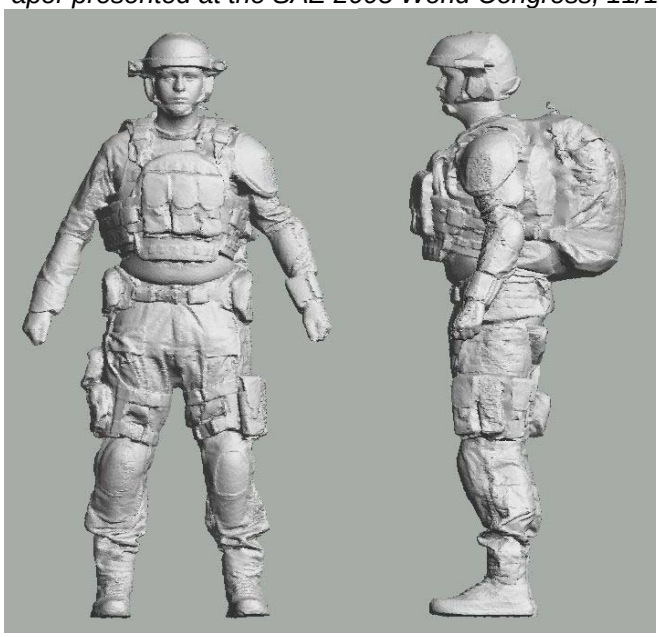

Figure 5. 3-D whole body scans of Soldier wearing a FFW block I ensemble.

VEHICLE CAD FILES

The next step in this approach confronts a problem that users of human figure modeling software have long struggled with: the availability of CAD files representing the design of the system. If CAD files exist, those provided to the human factors analyst may not represent the current version of the design.

Another aspect of the problem involves importation of CAD files into a usable format and file size. This problem usually begins because most equipment designs originate as CAD files created for the purpose of manufacturing the item. This results in having to use CAD files that are solid geometry models with parametric features that incorporate the material properties of the item to be manufactured. CAD models typically used for human figure modeling analysis are 3-D surface models. In other words, only the surface or boundary representation of the design is required. This difference in CAD model types means that a translation process is required to convert the solid model into a surface model or more specifically, faceted geometry when one is using a stand-alone human figure modeling package (see figure 6).

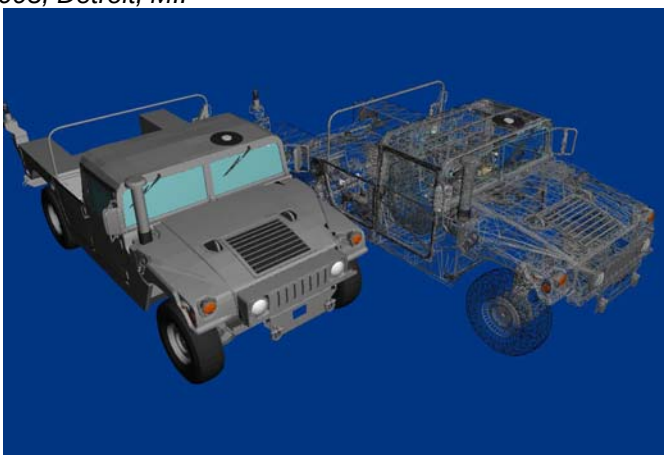

Figure 6. Surface model of a High Mobility Multi-purpose Wheeled Vehicle (HMMWV) displayed in both shaded and wire frame forms.

Thanks to processes such as stereolithography, many translators now exist to convert solid models into surface geometry. Stereolithography is used when rapid prototyping 3-D physical objects from a 3-D CAD surface model. It was one of the first commercial processes whereby a particular format was devised to interface with solid-modeling software packages. Most of the major CAD software vendors support the export of their model files into stereolithographic format.

Another challenge is the number of polygons used to represent objects in the file. Often, models that have been translated from solids to surfaces are not optimized and the surface model has many more surfaces than is required to efficiently define the object. For example, a single part in a vehicle design may have hundreds or even thousands of extra polygons after the translation of the file. If this problem is multiplied by the hundreds or even thousands of parts that comprise a vehicle design, computer graphics and computational resources can become overtaxed. Software known as “decimate” programs can be used to reduce the number of polygons on a surface model in an attempt to optimize the file. However, care must be exercised because reducing the polygon count may sacrifice necessary fidelity in the model. Many of the decimate programs will reduce the polygon count but at a certain point, these programs will also begin to remove detail and features of the model that the user would prefer to keep. That is why this step must be performed by someone who is familiar with the vehicle design; otherwise, highly desired design detail could be eliminated inadvertently.

Another problem with translated files manifests itself in the form of nonessential detail that may be included with the desired model file. In many cases when a CAD file for the design does exist, the human factors analyst receives a file of the entire system instead of just the components required for analysis. A typical example of this is a vehicle file that contains all the major subassemblies including every bolt, washer, and screw

thread as well as internal subcomponents. If the analyst is fortunate enough to have access to the CAD software that was used to create the original design, it may be possible to remove the unwanted detail by turning off the layers that these parts are assigned to and then to export the file. In many cases, however, the analyst is not so fortunate and the task of trying to cull unwanted detail from the design can become quite challenging and time consuming. If the analyst can establish contact with someone in the CAD department of the manufacturer, then the level of detail can be communicated directly to the person who is responsible for generating the files. The CAD operator at the manufacturer, in all likelihood, may be able to remove the unwanted detail in advance, and this can save the human factors analyst hours or even days of effort in performing the same task.

In some cases, the problem is missing detail rather than too much detail. For example, it is important that the CAD file include articulated joint definitions of movable parts that match the actual mechanical limits specified for that assembly. This information allows the human factors engineering to evaluate the effect of adjustable parts such as seats on accommodation. Joint definitions are frequently deleted from the files during the translation process or they may not have been defined. A recommended solution is to show movable parts at the extremes of displacement or rotation in the exported CAD file. For example, a seat pan can be depicted at its maximum fore and aft travel. If coordinates for centers of rotation (pivot points along with rotation and displacement limits) are known, they can be manually added as joints in the translated model.

The last consideration for the translation and optimization process is that it must be performed in a rapid and timely manner in order not to lag behind the design effort. If human factors design analysis is to be effective, the process must keep pace with the ongoing design or else struggle to make an impact when design options have become limited. Ideally, this is accomplished by the evaluation of human accommodation aspects of the design in an integrated process team (IPT) setting with design and human factors engineers working with the same files simultaneously. This approach is more efficient and reduces risk of redesign attributable to insufficient human accommodation when compared to design engineers inserting static figures as a space claim into their CAD files.

PERFORM ANALYSIS

Once the CAD files and the sized and clothed figures needed to begin the vehicle design analysis are available, the next step is to begin positioning the figures in the CAD files and putting them in the correct postures.

Positioning

One of the most common applications of human figure models is the evaluation of a workspace designed for a seated posture. However, realistically positioning seated human figure models can be difficult. A problem that users of human figure modeling software face is that the shape of the pelvis segment in the models remains fixed and does not change with the figure's posture. In many cases, some posterior point on the exterior of the pelvis segment is used to establish a relationship with the Seat Reference Point (SRP). See Roebuck et al. (1975) for definition of SRP. This method does not account for the stretching of muscles and compression of soft tissue on the bottoms of the thighs and buttocks for a seated posture. This in turn usually leads to a seated figure that is positioned too high and too far forward of the SRP. It is better, therefore, to use a skeletal landmark or joint center for positioning purposes instead of an exterior point on the surface of the figure's pelvis segment (figure 7). For the FCS approach, we recommend the location of the hip joint center be used

to establish the seated position of the figures. The location method is adopted from Reynolds et al. (1981) and studies performed by the University of Michigan Transportation Research Institute (UMTRI) (e.g., Reed, et al., 1999). The method uses proportions of the pelvic bone and the Ischial Tuberosity (IT) and Posterior-Superior Iliac Spine (PSIS) landmarks that can be found on the Jack model.

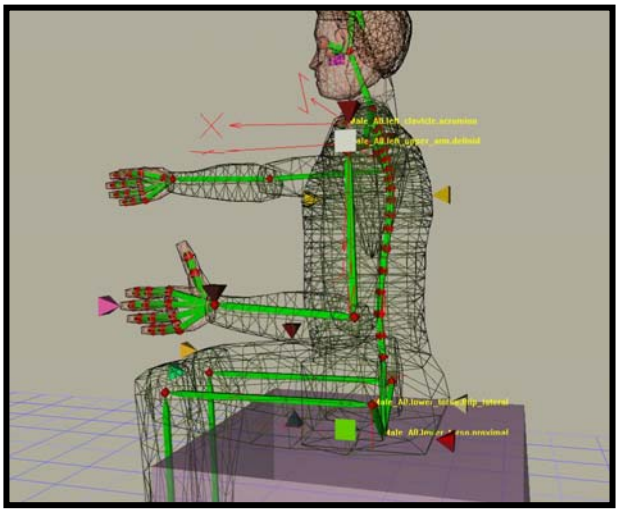

Figure 7. Male figure displayed in wire frame form to show Jack internal skeletal link model with joint locations.

Postures

After the figure has been positioned, the next step in the process is to determine a reasonable posture for the figure, based on the tasks and location assigned to that Soldier. These postures will vary between Soldiers assigned to crewstation positions and those soldiers who will be sitting in the squad location of the vehicle. In order to decide the best locations for the placement of displays and operational controls in a crewstation, a reasonable posture must be incorporated into the figures after they have been positioned. While there have been several studies linking posture to certain types of automotive seating, these data would be difficult to apply to armored vehicle seating because of the differences operating these two types of vehicles. For example, because armor protection is important to the survivability of an armored vehicle operator, direct vision is limited to a few fixed openings, sights or periscopes. Therefore the Eye Reference Point (ERP) is fixed and other elements must be designed to adjust to it. Although the ERP does allow for some head movement, the resulting viewable envelope is not the generous eyelipse available when one is looking out the windshield of an automobile. Seating must usually have greater height adjustment than an automobile so that an armored vehicle operator can view the outside environment through vision blocks or periscopes. When specialized clothing and equipment such as body armor, survival vests, and chemical protective ensembles (which also have an effect on the operational posture of the Soldier) are considered, the need to collect posture data that more closely correlate to armored vehicle operators is more evident. For the FCS program, a limited amount of posture data will be collected with a portable 3-D coordinate measuring device (figure 8). These measurements will be obtained with Soldiers wearing mission-essential clothing and equipment, sitting in prototype seating, and simulating required tasks.

Figure 8. Collecting aviator posture data with two 3-D digitizing arms.

Evaluating Layout

In the process of designing the arrangement of a vehicle operator's station, one must consider many factors. The most important of these considerations is to clearly understand the tasks the operator is to perform. As the layout begins, usually one element takes precedent over the others as a fixed starting point. It could be the foot pedals, the seat, a direction control or a vision constraint. Other elements then must have built-in adjustability to account for human variation and task performance. For example, an automobile may start with a fixed set of foot pedals, and the seat, steering wheel, and vision must be adjusted around that fixed element. A common starting point is the ERP. Once the ERP has been established, the distance down to the seat can be established if the sitting eye height of the tallest operator is known. We can determine the vertical seat adjustment range by knowing the sitting eye height of the shortest operator in the target audience mix. Sitting eye height is a measurement that is taken when a subject is sitting in a rigid upright posture. Most people do not sit this way in real life, so several other factors such as relaxed posture and cushion compression have a minor effect on this vertical range of adjustment. Human factors analysts need to convey to the design engineers the impact that human variations will have on hardware design and location. This is the point where several boundary manikins may be swapped into the crewstation to see where interferences might occur. If foot pedals or foot rests are part of the design, then the analyst needs to review the range of comfortable foot reach zones for a variety of operator sizes. If the comfort zones for small operators overlap with the comfort zones for large operators in different seat locations, then pedals placed within the overlapping area will likely be a good starting location for a common pedal. If the zones do not overlap, then adjustable pedals may be required. Again, the process includes reviewing several boundary manikins to check for clearance violations.

Fore and aft seat adjustment is usually a function of allowing all operators a comfortable reach or vision to controls or displays. Several human factors studies have been done over the years to convey the reach envelopes of an operator with respect to manual controls and displays. 3-D human figure modeling makes performing these reach evaluation much easier. An added advantage is that postural influences such as shoulder turn or torso bends are easily accommodated. Conveying the success or failure of a reach is convincingly illustrated by the selection of a strategic “camera” position within the 3-D environment. Numerous boundary manikins within the same 3-D environment model can repeat the same reach.

Application of Boundary Manikins

In addition to the seated crewstation analysis discussed earlier, the boundary manikins can be used in several ways. Boundary manikins derived from the central PCA form are helpful when design concepts are first being explored, to ensure that system components are properly integrated and to establish the ranges of body dimensions that a proposed system can accommodate successfully without additional sizes or adjustments. Manikins derived from extreme forms can be used as design limits and exit criteria for multivariate designs such as crewstations and integrated protective clothing ensembles because they capture the worst case scenarios for the critical design variables considered simultaneously. They can also be used to guide test subject sample selection.

It is important to realize that the multivariate center and boundaries of a particular accommodation envelope do not necessarily tell the designer how to successfully accommodate the users in between. In design problems involving clothing with multiple sizes, workstations with adjustments affecting two dimensions simultaneously, or clothing and workstation adjustment features with pre-determined adjustment "stops," knowledge of the sizes and shapes of boundary forms alone is not enough to complete a successful design. Additional statistical analyses are needed to optimize the sizing system, adjustment slopes, or adjustment stops to ensure that everyone inside the ellipsoid (i.e., percent of population for accommodation) is properly accommodated by the design. This may seem obvious in the case of developing a new vehicle; however, it has critical and often overlooked consequences for the evaluation and retrofitting of existing designs.

In the case of a vehicle crewstation, because the accommodation of subjects inside the design envelope depends in part on the geometry of the seat adjustment mechanism, one needs to be careful in drawing conclusions from boundary manikin tests alone when working backwards from an existing crewstation to an estimated accommodation rate. Failure to accommodate a boundary manikin of a particular (e.g., 90%) ellipsoid is sufficient evidence to suggest that the crewstation does not meet a 90% accommodation requirement. However, accommodation of all the 90% boundary manikins is not a guarantee that the 90% requirement will be met, because there may be subjects inside the design envelope who cannot be fit because the seat adjustment stops are too far apart and/or because the adjustment mechanism(s) geometry does not accommodate their body proportions. For this reason, testing should include crewstation checks with live subjects whose body dimensions are distributed throughout the required design envelope.

<u>Recommend Solutions</u>

As the human factors analysts identify design problems, they must also develop recommendations for addressing the problems. It is not sufficient to merely point out the problem. Analyses must be performed in a timely and efficient manner. An effective technique is to model suggested changes via the vehicle CAD files and export them back to the design engineers for consideration. The process of analyzing the designs must keep pace with the design process for the human factors analyst to have an impact. For the FCS program, these design recommendations are placed on a common server so that analysts and engineers on the Government, LSI, and contractor teams can have input into these design change recommendations.

Given the complexity of correctly positioning and posturing figures for analysis, it is recommended that human figuring modeling analysis tools designed specifically for this type of analysis be used. Custom figures or average sized manikins imported into engineering design CAD packages do not have the anatomical landmarks, joint definitions, and other critical parameters to yield valid results. Custom and imported figures cannot be used to evaluate dynamic space claims (i.e., how much room is required for an operator to perform all the motions required to do all their tasks?) as opposed to static space claims (e.g., how much space is required for a crewstation operator seated in one set posture?). These analyses are best performed by or with the help of an experienced a human factors analyst.

CONCLUSION

The common approach for human figure modeling analysis presented in this paper addresses sources of variability among the FCS team members and the approaches that they employ for human figure modeling analysis. Because it coordinates and distributes required activities among the FCS development team, duplication of efforts such as searching for the best data set, projecting the data, developing boundary manikins from those data, sizing human figure models and digitizing Soldier clothing and equipment are minimized. The approach clarifies expectations about the rigor and method considered acceptable for analysis so that developers are better able to estimate resource requirements for human systems integration. Discussions among team members will be focused more on design issues and less on the defense of analysis methodology.

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