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NO HATCHES ON HORSES: CREATING ACCURATE ENCUMBERED DIGITAL HUMAN MODELS TO ASSESS OPERATOR OR PASSENGER SPACE REQUIREMENTS

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ABSTRACT

For millennia the horse was the primary mode of transportation for mounted soldiers. Ingress and egress from a horse's back is straightforward, space claims are only related to the size of the saddle, and there were no confining walls to restrict what soldiers carried while on horseback. With the rise of the modern mechanized army, vehicle design became more complex. Critical to the effective design of vehicle interiors is an accurate model of the encumbered operator or passenger. Developments in three-dimensional (3d) scanning, computer-aided design (CAD) and other model creation capabilities make it possible to reproduce accurately the underlying human form and to add equipment encumbrances. This paper relates approaches taken in studies where Soldiers or aviators were modeled to define space requirements or reaches. Details of the modeling process, validation, and study results are given. Future research is discussed.

INTRODUCTION

Archeological evidence suggests the horse was first domesticated approximately 4000-3500 BCE in the Eurasian Steppes [1] [2] [3]. The added power, size, and mobility a horse provided was quickly adapted to gain an advantage in conflicts [4]. Whether ridden or pulling a load, horses remained the mainstay of mounted armies until the 20th century.

It is relatively easy to get on and off a horse. Invention of stirrups and saddle helped in that regard. The limit of what could be taken on horseback was determined by the size and shape of the rider and what could be strapped to the horse itself [5]. Thus, ingress, egress, and defining load space were straightforward. That all changed when horses were replaced by motorized vehicles. Walls or other structures confined occupants and constrained what may be either brought inside a vehicle as freestanding equipment or worn by an occupant. Door and hatch size became critical for efficient ingress and egress. Thus, vehicle interior design today is a complex trade-off between competing priorities. A useful heuristic for partitioning the problem space of vehicle interior design is to consider anatomy, geometry, and physics of the system. Anatomy refers to systems worn for protection from threats (blast overpressure, ballistic, translational, thermal, chemical, etc.). Geometry considers volume in terms of interior volume (occupant space, workstation space, reaches, etc.) and the volume the human occupies. Physics refers to dynamics, that is volume and its mass in motion. In this paper we are interested in analysis of volume and mass.

Representation of the human form has improved with developments in three-dimensional (3d) surface scanning and other digitizing modalities. Powerful computer graphics allow complex environments, like vehicle interiors, to be created and visualized digitally. These modeling and simulation capabilities make it possible to evaluate and weigh the impact of design decisions.

CREATING APPROPRIATELY SCALED DIGITAL HUMAN MODELS

Development and validation of digital human models (DHM) is the key component to effective vehicle interior modeling and simulation. The major commercial digital human modeling software packages used for human factors evaluations such as Jack (Siemens PLM), RAMSIS (Human Solutions), Delmia-Human (formerly Safework), as well as newcomers such as Santos (University of Iowa/ESI) provide premade DHMs whose size/shape may be selected based on percentile score or other criteria. They also allow creation of new forms from anthropometry generated by outside analysis. Selection of body dimensions to drive DHM size/shape must be made with care. Pre-existing datasets and percentile ranges may or may not cover the population in question. When user-generated anthropometry input is available, it is best to enter as many body dimensions as possible to minimize the number of body dimensions estimated from built-in regressions. Regressions, like the percentile values, may have been computed from a population different from the target population of study. For example, the Delmia V5 Human takes up to 103 measurements and imputes missing values based on 1988 US Army Anthropometric Survey (ANSUR) regressions [6]. Further, given that most evaluations utilize models at the extremes of accommodation, securing the appropriate representative anthropometric data for a user population becomes paramount.

The phrase "5th to 95th percentile" has entered the engineering lexicon as shorthand to describe a 90% population accommodation envelope. A percentile is a univariate value; however, seat adjustments, displays, controls, and the like must accommodate many body dimensions simultaneously to be effective. As [7] and others have pointed out, when simultaneous accommodation is required, univariate percentiles are not appropriate to set boundary conditions [8] [9]. It is better to establish body size/shape parameters with multivariate statistical analyses such as Principal Components Analysis (PCA) or Factor Analysis (FA). A number of papers are available that demonstrate the application of PCA to establish worse-case anthropometry for engineering applications [10] [11] [12].

Generating a custom DHM for a given application was outlined by [7] for the Jack V4 human figure. The approach is not unique to the Jack system and may be applied to DHMs in other simulation environments with minor changes to accommodate input variables. Essentially, the method is to input target anthropometry into the simulation's data editing feature and adjust the resultant DHM if necessary (Fig. 1). The adjustment step is critical. Some of the dimensions are cumulative. For example, in Jack sitting height is influenced by several variables- sitting eye height, acromial sitting height, and elbow height. If one of the constituent values is changed, the program may change the other values according to a built in regression function. Segment values may be locked but some small change may be required to get all segments to link up correctly. The markers are stored with the DHM as a visual reference check against unintentional changes in dimensions (Fig. 2). Once all anthropometric data have been input a final check should be done to ensure all segment lengths are correct.

Another approach to DHM creation is to use a three-dimensional (3d) whole body surface scan as a template against which the DHM is scaled. Anthropometry may be extracted from the scan or measured directly and input as described above. The resulting DHM is compared to the scan to check how closely they match (Fig. 3). Adjustments are made to the DHM until the desired level of fit is achieved.

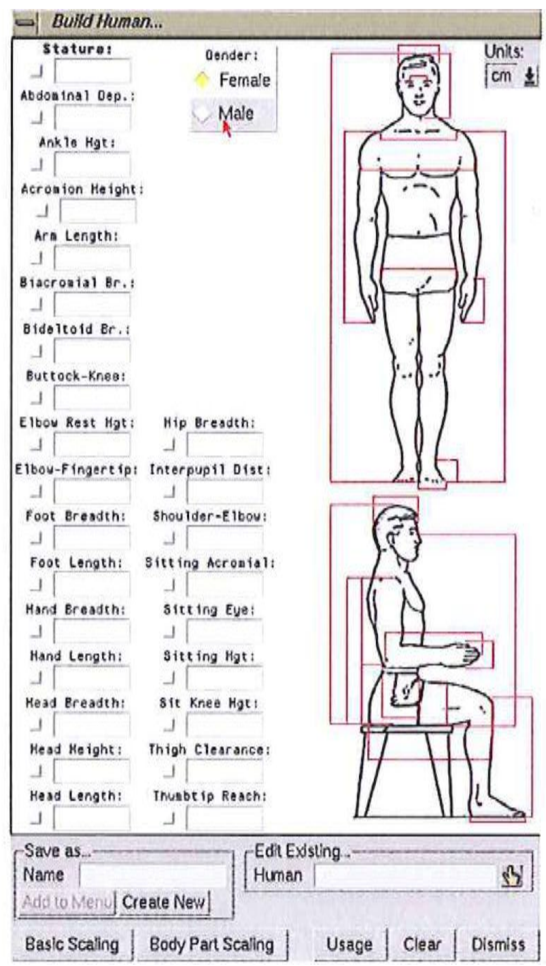

Figure 1: Jack V4 anthropometry data input sheet.

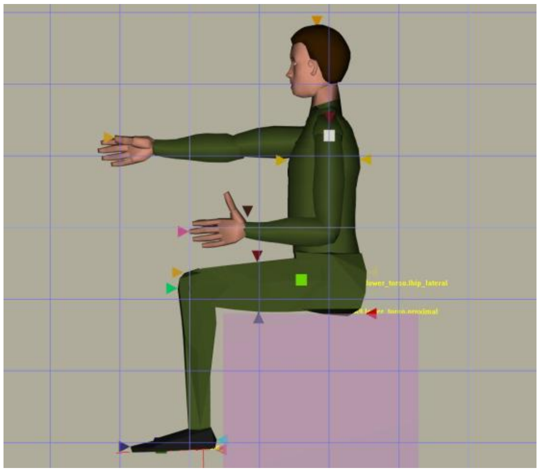

Figure 2: Jack DHM showing landmark points for assessing baseline anthropometry.

CREATING ENCUMBERED DIGITAL HUMAN MODELS

While clothing and encumbrances are disregarded for many types of office and commercial workspace designs, they are an important factor to consider for military systems where space is often at a premium and the additional clothing and equipment can add significant weight and bulk to each individual. Some typical examples include multilayered ensembles that provide protection against nuclear, biological and chemical threats, clothing to operate in extreme cold weather environments and body armor for ballistic and fragmentation protection. Additionally, load bearing vests and packs are worn to help transport sustainment supplies, along with advanced tactical equipment such as communication gear, components for night-vision and thermal imaging capability, as well as lasers for range-finding and target designation. Clearly, clothing and equipment items of this nature must be accounted for in the workspace designs of military systems if specified accommodation goals are to be met.

Creating an encumbered DHM has been a challenge in the past. Often, 3d digital equipment models were not available.

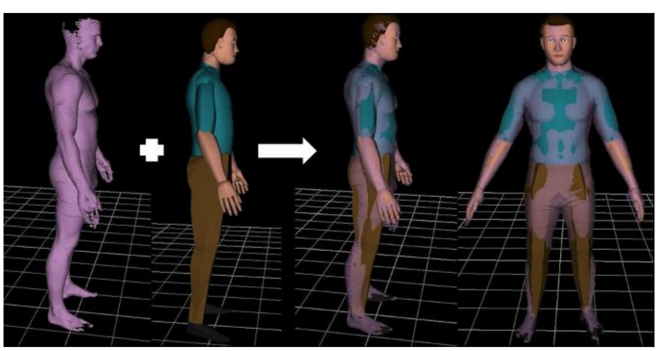

Figure 4: Adjusting DHM anthopometry by comparing the model to the baseline 3d scan.

If models were available, getting them into the correct format, the appropriate resolution and scale, and attaching them to the DHM was not easy. Recently, many of the obstacles have been overcome. A concerted effort is being made to create 3d models of clothing & equipment commonly worn by Soldiers. A drag-and-drop capability to place items in an approximate position is available for most DHM environments.

What are the items and where should they go? To answer the questions we have turned to 3d whole body surface scanning. Defining load components and how they are distributed on the body is a task for a subject matter expert (SME). Figure 4 illustrates SME defined equipment and its distribution on a Soldier body relative to the digital model. Photographs are one means to capture where items are worn on the body, but a direct comparison between an encumbered Soldier and his/her simulated counterpart is better. Such a comparison is possible if a 3d whole body surface scan of the encumbered subject is set as a reference. As was the case when a semi-nude scan was used to define DHM size/shape, a 3d surface scan and associated clothed anthropometry may be used to generate an encumbered model. The progression from unencumbered to encumbered DHM is illustrated in Figure 5 for a standing figure. The same approach may be used to create a seated DHM. Reference markers are used to maintain correct anthropometry. Table 1 provides results from a test case where a Jack DHM was matched to an encumbered 3d scan. Measurement error values from a study of clothed anthropometry [13] serve as a reference of DHM quality. Differences between five body dimensions of the live subject and those of the Jack DHM exceed measurement error but not by much. Thus the approach described produces accurate DHMs for the next step in the process, analysis within a digital environment.

Figure 3: SME defined equipment and its distribution on a Soldier body relative to the digital model.

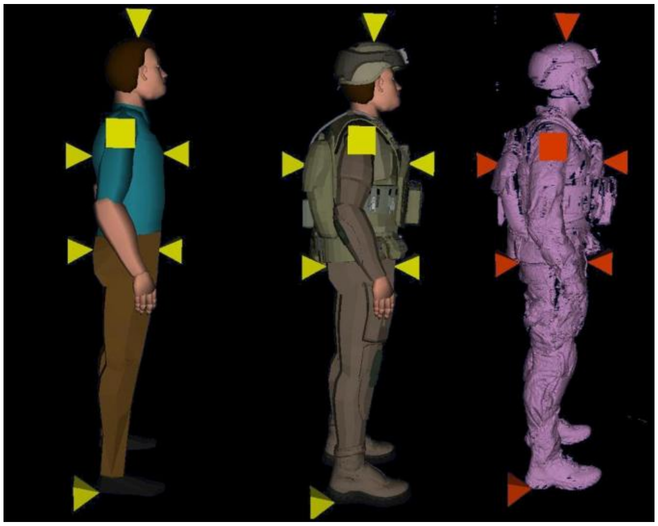

Figure 5: Creating and validating clothed anthropometry and CIE position of an encumbered DHM.

ANALYSIS OF SPACE, REACH AND OTHER HUMAN FACTORS MEASUREMENTS

Once the occupant has been modeled, the DHM may be placed into a digital environment. Generating a digital environment is a considerable task in its own right. The extensive use of CAD in vehicle design provides a resource; hand-scanners may also be employed to create low resolution models which are often appropriate for human factors analysis.

Space claims are straightforward to compute as the bounding box around the DHM in a given posture or as the volume of the DHM mesh. Hatch size for in/egress may be based on overall DHM volume for a given escape position. Operating controls, including those needed to get into or out of a vehicle, involve reaches and other movements that are more difficult to quantify. [14] conducted a verification and validation study of cockpit ergonomic assessment using five simulation environments- RAMSIS, Jack v2.1, Safework (prior to purchase by Delmia), Boeing Human Modeling System v3.5.2, and COMBIMAN v11. All systems yielded problems in modeling reach tasks. The main sources of error identified included incorrect initial positioning and posture, lack of DHM tissue and seat deformation, poor inertial reel restriction model, incorrect DHM anthropometry, and no protective equipment on the DHM. The authors suggested a combination of live subject study and simulation may overcome the observed shortcomings of simulation only.

The last two challenges to accurate simulation of reach tasks are corrected with improved DHM software capabilities. Matching a DHM to a 3d scan as described above ensures appropriate anthropometry. Recoding eye height, foot and knee position, and other body segment locations in a live subject provided data to adjust DHM seat and tissue compression. [15] also identified a minimum number of reach points for cockpit evaluation- three elevations and 5 azimuths). Quantifying reach limits with the restraint system engaged solves the problem of modeling inertial reel effects and other seat limitations, and defines initial seat position. The approach outlined works well for cockpit reach evaluation. The method is easily modified to accommodate other vehicle interior environments.

Table 1. Comparison of encumbered DHM to direct measurements froma live subject (units=millimeters).

Variable	Jack Figure with FFW Clothing and Equipment Models	3D Whole Body Scan of FFW Equipped Subject
AD Abdominal Depth	493	487
BDB Bideltoid Breadth	542	533
BKL Buttock-Knee Length	645	636
CHD Chest Depth	414	412
EHS Eye Height Sitting	1211	1209
FFB Forearm-Forearm Breadth	736	733
KHS Knee Height Seated	616	608
PH Popliteal Height	440	458
SH Sitting Height	1354	1356

POPULATION LEVEL ANALYSIS

Thus far we have described methods to define anthropometry for a DHM with direct body measurements or from a 3d scan. We have shown that CIE may be added to the DHM and we demonstrated how initial boundaries for reach task simulation may be established. The next step in a full analysis of vehicle interior design is to define and run DHMs that represent a user population.

To avoid problems caused by applying univariate percentiles to functional systems that are multivariate in nature, PCA is recommended. Considerable care must be taken when selecting body dimensions for analysis. Body measurements related to functional requirements are considered first: eye height, thumb tip reach, overhead reach, functional leg length, etc., for example. Then there should be body measurements which represent important body segments and body mass (weight, circumferences, e.g.). One may be tempted to run an “everything and the kitchen sink” PCA, but the model will be overly complex and the results difficult to interpret and apply.

The point of a PCA is to establish body dimensions for boundary cases [10] [11] [16] [6] [17]. As a data reduction method, PCA scales and rotates the subject data so as to identify the mutually orthogonal directions of decreasing variance (Reyment et al. 1984). The directions or principal components (PCs) may be plotted in standard coordinate space. Boundary cases are defined from the surface of an equal frequency ellipse (EFE) for the two factor case, or ellipsoid in the three factor case which encloses some percentage of the subjects in analysis [18]. (There is no clear-cut method to define how many PCs to retain in an analysis [19]; however, a general rule-of-thumb is to keep enough PCs to account for approximately 90% of the sample variation. For most analyses of human body dimension, three or four PCs are usually enough.) A 90% EFE is commonly used [16] [6] [17], but selection of other percentages is not excluded. Any number of boundary cases may be computed, generally the major axes are selected, four for the 2d EFE and six for the 3d EFE. Additional boundary cases may be selected from the EFE surface, along equal arcs for example (Fig 6). [6] provides a concise explanation of how to determine boundary cases.

Boundary forms are “worst case” engineering scenarios. They represent combinations of body proportions at proposed design limits. Thus, the logic goes, if an item concept has the adjustability to accommodate the boundary cases then the final product will likely be successful. However, PCA is only an approximation and is only as accurate as the data provided. It is impossible to obtain all the variables needed to predict 100% accommodation. Disaccommodation may occur for subjects inside the design envelope who cannot be fit. Seat and pedal adjustments are prime examples where adjustment stops may be too far apart and/or the geometric relationships of the adjustment mechanism(s) may not accommodate body proportions. For this reason, interior checks with live subjects whose body dimensions are distributed throughout the required design envelope are always desirable. As indicated by [15], recording a subject going through the fifteen reaches prescribed (by three times) establishes a reach envelope and defines seat and tissue compression. The addition of a few more subjects bounds the problem further. The difference in reach between baseline and under seat restraint and encumbered conditions provides further adjustment for simulation with a DHM.

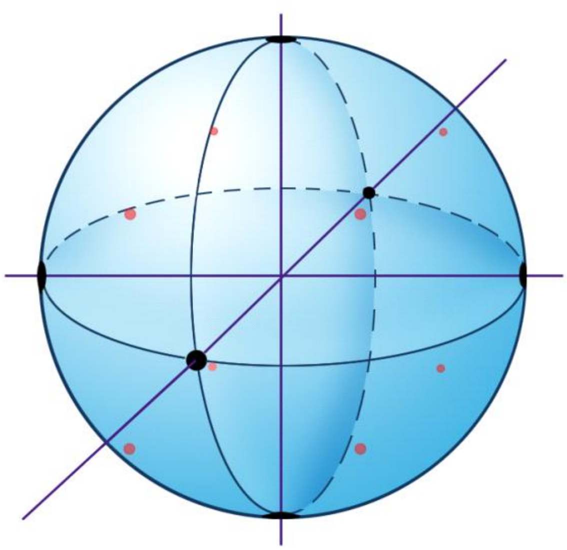

Figure 6: Map of boundary cases from PCA.

Live cockpit testing has its parallel in measurement of clothed anthropometry. [13] demonstrated clearly that increased encumbered volume through the addition of CIE is nearly constant across subjects. This makes sense if one considers that CIE items added to the body tend to be the same for all subjects, for example an ammo pouch or a canteen; or do not add thickness, a size large ballistic plate is longer and wider but not thicker than a size small plate. Thus, every subject wearing the same ensemble will tend to have about the same increase in encumbered volume.

Live test data combined with anthropometry from PCA defines a morphological space for simulation. Creation of a family of DHMs of the appropriate anthropometry with the appropriate gear is now possible. An example of a family of Jack figures is given in Figure 7. Live test data are used to position and adjust the DHMs prior to evaluation of the vehicle interior. The family of models captures more accurately the variation in body size and shape of vehicle occupants. Reaches, clearance, vision, and other important factors related to vehicle operation may be evaluated and adjustments to interior design made early in the design process.

ANTICIPATED IMPROVEMENTS IN DIGITAL HUMAN MODELING FOR VEHICLE DESIGN

The volume of an encumbered DHM may be reported as a bounding box or as total volume of the DHM. Encumbering a family of DHMs provides multivariate cases to evaluation a single seat, or select sizes for a bench seat configuration. In the bench seat situation, engineers typically select the bounding box of the “largest” DHM (often described as the 95%ile). However, the chance of all large occupants sitting on a seat is rare. Recently, two of us (CCG and BDC) investigated a bootstrap-based method to obtain a more realistic space claim value for bench seats. Briefly, the method utilizes bootstrap selection of N subject, where N is the estimated number across a seat, from a large anthropometric data set (US Army males in this case). For

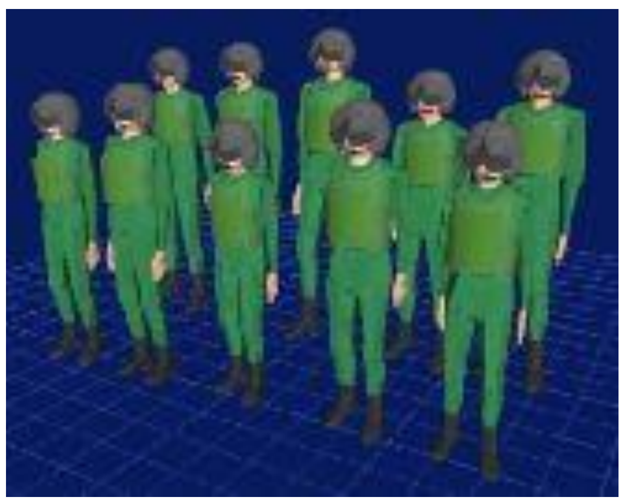

Figure 7: Illustration of a family of encumbered DHMs.

each bootstrap simulation, design values are estimated (e.g., buttock-knee length, sitting height, bideltoid breadth) that capture a percentage (e.g., 90% or 95%) of the N subjects. The anthropometry of the selected subject is then adjusted to include encumbered volume. The result is a statistical representation of the total occupant volume for a given bench seat design. Additional work is needed to refine the method but initial results are very promising. The approach may be used to model small groups, such a squad, for multi subject simulation such as force on force, modeling the impact of weight distribution on mission performance, and others.

Within the three-way partition of the problem space described above, Anatomy is accounted for by the protective systems worn by the DHM, Geometry is the volume of the DHM plus CIE, but what about Physics? Has the mass of the DHM changed with body scaling or the addition CIE? The two simulation packages we are familiar with, Jack and Delmia, contain a center-of-mass (COM) location and associated weight that changes as the baseline body shape changes. However, for a given baseline DHM adding CIE increases volume and weight but does not change the position of the COM. In addition, moments of inertia (MOI) are not computed. The additional weight certainly has an impact on movement, but mass distribution also has a strong effect on balance, agility, acceleration, deceleration, bending, reaching, etc. [20]. Researchers at the Virtual Soldier Research (VSR) Center, University of Iowa, have developed a DHM, "Santos™", which is capability of adjusting COM and MOI to accommodate the addition of CIE [21]. For example, if a 40 pound pack is added to the DHM the CG and MOI are adjusted to accommodate the increased load on the subject's back. Mass distribution data increase in importance as simulations move to dynamic models.

Added CIE is registered as an increase in volume over the baseline figure. However, there is limited collision detection or collision avoidance. Again, researchers at VSR are implementing collision avoidance and collision detection. Thus, in a reach task with an object between Santos™ and a target, the DHM will reach around the obstacle, if possible. Critically, collision avoidance includes self avoidance. That means not only does encumbrance change the CG and MOI of the DHM, it also means a reduction in range-of-motion (ROM). Overall, the VSR simulation will have the capability of interacting with the environment in a much more complex and rich way. An egress simulation, for example, will include evaluation of vision, reach, strength, and snag in the form of collisions with CIE.

SUMMARY AND CONCLUSIONS

We have described how DHMs may be constructed to represent accurately the user population of a vehicle for interior design human factors evaluation. The DHMs begin with the latest population anthropometry. The addition of 3d scans provides detailed surfaces and limb segment verification, and is a resource for correct placement of digital versions of CIE. A population of DHMs may be constructed based on anthropometry of "worst cases" defined using the results from PCA of body dimensions which reflect functional requirements of the design. Final adjustments to DHM positioning and restrictions due to the addition of CIE or to seat restraints are made through small-scale testing of live subjects. Exercising the DHMs in a simulated environment provides important information on how users will function within the interior space. The detailed and accurate representation of operators and occupants ensures the resultant evaluation will be of high value.

Capabilities in near-term next generation of DHM software will include simulation of dynamic scenarios, will have collision detection and collision avoidance capabilities, and will provide a software platform for rapid update of DHMs and their gear as CIE technology advances and mission requirements change. We look forward to working with the designers and engineers of the next generation transportation systems.

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