Applications of Human Factors in Space

The main question for human factors practitioners is to determine if the user population can be accommodated within a design. Given the wide range of variables feeding into a design, just one of which is human factors, oftentimes designers will have restrictions that may potentially impact the level of accommodation. This paper focuses on two case studies where there have been impacts at the design level that may be detrimental to the ability of the design to meet certain criteria. The studies use novel approaches to determine what, if any, changes in population accommodation levels have occurred and what factors are important when manipulating the design in the future. The results of these studies provide a backbone for future analyses when working with design considerations.

INTRODUCTION

When designing any human-object interface, it is critical to properly quantify the limitations and capabilities placed on humans within the structure, mechanism, or procedure. Human factors is concerned with the definition of these qualities through all stages of development and evaluation of a design.

The Anthropometry and Biomechanics facility (ABF) at NASA Johnson Space Center is at the forefront in providing necessary design requirements and limitations for both the future space vehicle and suit design. The proper usage of human factors should lead to an increase in total system performance and reduction of developmental and lifecycle costs of design prototypes. The ABF acts as a central resource for analysis related to the accommodation of the target population. It developed and maintains the population database for the astronaut corps, establishes the critical anthropometry requirements for the future cockpit and space suit dimensions, supports prototype development efforts by providing in depth analyses regarding population accommodation, and evaluates the end stages of the designs to ensure all requirements have been met.

The challenges facing the design of the vehicles and suit are somewhat unique in complexity, yet the fundamental methodologies are applicable across the many disciplines that utilize human factors. The ABF has taken unique approaches to some common human factors problems in order to provide much needed information to designers.

HUMAN FACTORS APPLICATIONS

The ABF has encountered two primary challenges of human factors work, namely to reduce uncertainty in design accommodations and to verify that the design meets certain criteria. Since the space program is in the early stages of developing a new set of crew interface devices, the focus has been mostly on the former human factors goal at this point in time.

In the requirements defined by the Human System Integration Requirement (HSIR) document, all crew interface devices must meet the accommodation levels encompassing the 1st percentile American female to the 99th percentile American male (HSIR, 2007). Typical applications of human factors focus on accommodating the entire range of expected users for any system and one would adhere to these limitations across all stages of design. Whether it was a door, glove, or width of a walkway, the entire range of population would need to be accommodated and thus are hard restrictions in the design. It must be borne in mind that openings of the hatch as well as other key dimensional parameters are more severely constrained in a spacecraft due to space and volume limitations when compared to similar features for Earth-bound designs. As an example, the height of the hatch may not allow for extra room in order to maintain the integrity of the shell. Due to the multivariate and oftentimes complex issues that arise in design, novel approaches to determine if the design meets certain accommodation criteria are necessary. This paper will focus on two such analyses in which accommodating to the extreme ranges of the population was detrimental to the end design and the use of novel approaches in the determination of new restrictions in accommodation was necessary.

NOVEL APPROACHES TO UNIQUE HUMAN FACTORS APPLICATIONS

Case Study #1: Crew Weight

The Orion crew module will be required to carry 4-6 astronauts along with associated supplies up to both the International Space Station and on to lunar orbit. In typical human factors applications, one would seek out the extreme value to ensure proper accommodation of all crewmembers, specifically the 99th percentile. But herein lies the problem; if four 99th percentile value masses are used as a total mass, the resulting value is 440.8 kg for a four crew configuration. This number is far too high to use as a design requirement for crew weight, and illogical since there is a very low probability that four 99th percentile male crewmembers will fly at any given time. To provide an alternative value, the ABF performed a Monte Carlo simulation.

Methods. The Monte Carlo method is a simulation technique using random numbers, and was employed specifically in order to handle the binomial aspects of the combined male and female anthropometric data. The Monte Carlo essentially generates a new population by randomly selecting individuals from an existing population over a certain number of iterations. The simulation was applied first by choosing the number of iterations to run through for the analysis. The increasing iterations should result in a convergence of the results. Iterations of 10,000, 50,000, and 100,000 were chosen to run the code, and a definitive convergence was found around 10,000 iterations depending on the initial database size. Next, a ratio of female to male subjects was determined; this number was selected based on the current active duty astronaut population, excluding management and non-U.S. personnel, resulting in a percentage value of 18.5% females. Crew compositions of two, three, four, five, and six crew members were used to tally into a total group weight.

For each iteration (1-100,000), a uniformly distributed random number between 0 and 1 was selected; if this random number was less than the value of 0.185 (the fraction of active duty females) the female anthropometric database was used. If not, then the male anthropometric database was used to select a subject. A single subject was selected randomly from the database of interest and the resulting weight was tallied into a total group weight. This was repeated for each crew composition of interest for a single iteration, and the resulting group weight was recorded in a new database. As an end result, a new database consisting of 10,000 randomly selected group weights was generated for each crew configuration of two, three, four, five, and six crewmembers. The results were plotted as a distribution to determine the mean and standard deviation.

The database of anthropometry used for the analysis was the 1988 Anthropometric Survey of Army Personnel (ANSUR), truncated between the ages of 30-51 yrs (Gordon, 1988). The ANSUR database was projected to estimated 2015 values based on growth adjustments on the measurements from two basic sources of secular growth information: United States Air Force and the Department of Human Health National Health and Nutrition Examination Survey (NHANES), creating the HSIR database (HSIR, 2007). This HSIR database of both male and female data was truncated by removing all males weighing greater than the 99th percentile weight as well as all females weighing less than the 1st percentile weight. This truncated database is the representation of the astronaut population and incorporated the percentile limitations of weight as stated within the HSIR document (HSIR, 2007).

Results. The results for the Monte Carlo simulation with 10,000 iterations across the different crew configurations yielded means and standard deviations as shown in Table 1. For a single crew configuration, the HSIR weight requirement is provided for reference. The 95th percentile value of each crew composition was selected to use as a final total crew mass designation. An example of a weight distribution generated by the Monte Carlo for a four crewmember composition using 10,000 iterations is shown in Figure 1.

Table 1: Monte Carlo results as a function of crew composition

Crew Number	Mean (kg)	Std. Dev (kg)	95th% percentile (kg)
1	X	X	110.2 *
2	157.1	18.0	186.8
3	235.8	22.2	272.3
4	314.2	25.5	356.2
5	393.1	28.7	440.4
6	471.7	31.5	523.5

*Maximum HSIR single crew mass

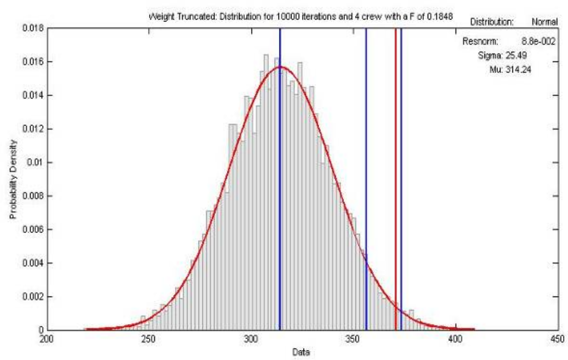

Figure 1: Distribution of weight (kg) for four crew members using a Monte Carlo simulation and 18.5% of females in the population using 10,000 iterations.

Discussion. The 95th percentile value of each crew configuration was selected to feed forward into design requirements of the crew vehicle based on discussions on previous weight limits and analyses related to expected probability of accommodation. However, these levels can be modified in the future based on the crew selection process and final design limitations. For instance, the database was originally truncated only using weight; for future studies other critical dimensions can be incorporated into the truncation and the resulting total crew mass estimate decreased. In addition, if the percentage of females in the astronaut population increased due to crew selection, the Monte Carlo simulation can be performed with this new percentage of females, thus changing the total crew mass values. In the same vein, if the crew weight requirements in the vehicle must absolutely be lowered to a certain total value due to cost or other design considerations, then the Monte Carlo simulation can be re-examined by determining the probability that any given crew would be able to meet that weight requirement as a function of restriction level and what new weight restriction would be necessary.

The usage of the Monte Carlo simulation has the benefits of incorporating the multivariable nature of anthropometric data while providing a useful tool to weigh against other design considerations. It provides a realistic examination of many human factors concerns and can be used in a variety of ways to communicate the impact of decisions impacting the overall design. The Monte Carlo process can be applied to other design engineering scenarios that have to weigh the cost benefit aspects of accommodation, for instance car or airplane designers.

Case Study #2: Clothing and effects of space on the human body

The ABF was initially asked to identify what percentile crewmember would fit in Seat 4 of the Orion module, based on the HSIR requirements and assuming that Seat 1 must accommodate a maximum 99th%ile male for seated height. The ABF was provided with a layout (Figure 2) detailing the space allotment for both crewmembers. According to the drawing, total allotment of space to accommodate both the crewmembers' seated height for Seats 1 and 4 was 226.6 cm.

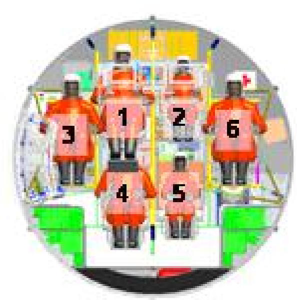

Figure 2: Seat arrangement for Seat 1 and Seat 4, given the current configuration of the CEV and assuming that Seat 1 must accommodate a 99th%ile male.

Two factors impact the seated height measurement; spinal elongation and clothing effects. Spinal elongation of approximately 3% of the total stature height (NASA 1024, 1978) has been observed to occur in crewmembers during space flight. Spinal elongation is postulated to be due to the extension of the spinal column due to fluid in the intervertebral disc space as well as decreased curvature of the spine due to the lack of gravity. The seated heights for both crewmembers must reflect the effects of this 3% spinal growth adjustment as well as the change in seated height going from minimally clothed to an unpressurized suit. The concern is accommodation on the re-entry portion of the mission, after the effects of microgravity have been compounded. In addition there were several different suit configurations tested, and the overall impact on crew accommodation was needed.

Methods. The study focused on the effects of spinal elongation, suit configuration, and seated height restrictions on crew accommodation. Spinal elongation was tested under two conditions; no spinal elongation and 3% spinal elongation. Suit effects consisted of four conditions; a baseline configuration, a baseline plus a bearing that added 7.6 cm to seated height, a baseline plus a helmet configuration that added 7.1 cm to seated height, and a baseline including the addition of both the 7.6 cm bearing and 7.1 cm helmet configuration. For the purposes of this report, the anthropometry used was the limit of 99th percentile male seat height based on the HSIR database (HSIR, 2007).

The ABF developed a mathematical equation that can be applied to any individual within the reference population. This equation started off with the assumption that the spinal elongation effects (3% of stature) are applied solely to the seated height measurement along with the effect of wearing the suit. The resulting equation to calculate the effects of 3% spinal elongation as well as suit effects is presented in Equation (1) where the μ represents the mean, σ is the standard deviation, K is the standard Z score, Δ is the suited to unsuited ratio of sitting height, the subscript SH represents sitting height, and the subscript S represents the stature, (Table 2)

$$AvailableHt = [\mu_{SH} + K\sigma_{SH} + 0.03(\mu_S + K\sigma_S)] * \Delta_{SH} \quad (1)$$

Table 2: The mean and standard deviation for the seated height and stature for unsuited conditions based on the HSIR requirements

	Male Seated Height Unsuited	Male Stature Unsuited
Mean μ (cm)	92.8	178.6
St.Deviation σ (cm)	3.6	6.8
Ratio Unsuited to Suited Δ	1.11	X

Results. The results from the analysis for both spinal elongation and suited effects are presented in Table 3.

In regards to the suited effects, the baseline configuration accommodates all crew for both Seats 1 and 4, regardless of spinal elongation effects. However when the effects of the helmet or bearings are incorporated, the level of accommodation drops dramatically, compounding further with spinal elongation. In a prime example, three of the four suit configurations accommodate all crewmembers (>99th percentile) in the 0% spinal elongation condition, yet in the baseline with bearing and helmet bailer bar configuration the level of accommodation for Seat 4 drops to a mere 15.7th percentile male seated height value.

The effects of spinal elongation have a severe detriment on accommodation levels. In the worst case configuration, the baseline with additional height due to bearing and helmet bailer bar configurations, if a 99th percentile male is in suit 1 no one can be accommodated in suit 4. For the baseline plus helmet bailer bar configuration, the accommodation level for Seat 4 is reduced from over 99th percentile to just above a 38th percentile male in seated height.

Table 3 Effects of spinal elongation on various suit configurations

	Baseline plus Bailer Bar (2.8") only	Baseline plus 3inch Bearing & ACES Bailer Bar (2.8")	Baseline	Baseline plus Bearing (3") only
0% spinal Elongation				
S1 Male Percentile	99.0	99.0	99.0	99.0
S4 Male Percentile	99.7	15.7	100.0	99.5
S1 Height (cm)	112.3	119.9	105.2	112.8
S4 Height (cm)	114.2	106.6	121.3	113.7
3% spinal Elongation				
S1 Male Percentile	99.0	99.0	99.0	99.0
S 4 Male Percentile	38.8	0.0	99.9	29.9
S1 Height (cm)	118.8	126.4	111.7	119.3
S4 Height (cm)	107.7	100.1	114.9	107.2

Discussion. The analysis detailing the spinal elongation and suit effects on seated height were provided to the designers. Additional analyses were performed, focusing on various suited configurations as well as the impact of different height limitations. In addition, a random sampling of crew, similar to the Monte Carlo analysis from Case Study #1, was performed to provide estimates on how often the issue of a 99th percentile male in Seat 1 would impact the crew configuration. Ultimately, the result was a modification of the allowable seated height for crew selection.

The benefits of this analysis are that it combined both spinal elongation effects and suit effects into a simple reporting tool, allowing the designers to see the sometimes severe impact of their design choices for both the suit and cockpit design. Oftentimes a design simply cannot meet accommodation level requirements, due to cost or engineering concerns. The benefits of this analysis is that it combines all variables under consideration and ultimately allows one to determine what restrictions in accommodation levels to put in places as a result.

SUMMARY AND CONCLUSIONS

Due to the fluid nature of design and the impacts of other design considerations, it may not be feasible to adhere to the desired accommodation range. At that stage, human factors practitioners must be involved to quantify how the design impacts the levels of accommodation and to provide important feedback to the design process. This requires a novel approach at times, but will be beneficial to both engineers and designers alike in achieving the initial goals to the full extent possible.

This paper demonstrated two such novel approaches in addressing these human factors concerns. They attempted to answer the question: if the design does not accommodate the extreme, what does it accommodate? However, the analysis also provided the means to determine how often the accommodation restrictions would be an issue. This information is fundamentally necessary to feed into the design process and will have impacts on decisions and restrictions surrounding the design in the future.

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