CHAPTER XX

Model for Predicting the Performance of Planetary Suit Hip Bearing Designs

Matthew S. Cowley[1], Sarah Margerum[1], Lauren Harvill[1], Sudhakar Rajulu[2]

[1]Lockheed Martin
1300 Hercules
Houston, TX 77258
matthew.s.cowley@lmco.com

[2]NASA Johnson Space Center
2101 NASA Parkway
Houston, TX 77058
sudhakar.rajulu-1@nasa.gov

ABSTRACT

Designing a space suit is very complex and often requires difficult trade-offs between performance, cost, mass, and system complexity. During the development period of the suit numerous design iterations need to occur before the hardware meets human performance requirements. Using computer models early in the design phase of hardware development is advantageous, by allowing virtual prototyping to take place. A virtual design environment allows designers to think creatively, exhaust design possibilities, and study design impacts on suit and human performance.

A model of the rigid components of the Mark III Technology Demonstrator Suit (planetary-type space suit) and a human manikin were created and tested in a virtual environment. The performance of the Mark III hip bearing model was first developed and evaluated virtually by comparing the differences in mobility performance between the nominal bearing configurations and modified bearing configurations. Suited human performance was then simulated with the model and compared to actual suited human performance data using the same bearing configurations.

The Mark III hip bearing model was able to visually represent complex bearing rotations and the theoretical volumetric ranges of motion in three dimensions. The model was also able to predict suited human hip flexion and abduction maximums to within 10% of the actual suited human subject data, except for one modified bearing condition in hip flexion which was off by 24%. Differences between the model predictions and the human subject performance data were attributed to the lack of joint moment limits in the model, human subject fitting issues, and the limited suit experience of some of the subjects. The results demonstrate that modeling space suit rigid segments is a feasible design tool for evaluating and optimizing suited human performance.

Keywords: space suit, design, modeling, performance

1 INTRODUCTION

Designing a space suit can be very difficult with the numerous and complex requirements, which include the constraint that a crewmember be able to move without being overly encumbered by the suit. To verify that new suit designs meet these requirements, prototypes must eventually be built and tested with human subjects. However as is common with design, numerous iterations will occur before the hardware is finalized and designing a suit to uphold human performance requirements often negatively affects the suit’s complexity. These factors often lead to quickly escalating development costs as multiple prototypes are built and tested.

The current planetary-type space suits use complex and multi-component joints with rigid segments and bearings. These rigid segments allow the suit joint to move while maintaining a constant air volume (and therefore air pressure) inside of the suit. Because of the difficulty in modeling the flexible cloth components in the suit as well as the compound motions needed by the multi-bearing joints, computer models have rarely been used in the development phase of suit hardware. With increases in the amount of quantitative data of suited human performance and in modeling technologies, modeling complex space suit systems has become much more feasible. Using hardware design models early in the design phase of suit development would be very advantageous, and allow virtual, concurrent engineering to take place (Cutkosky, Engelmore, Fikes, 1993).

The purpose of this study was limited to specifically evaluating a hip joint model of the Mark III Technology Demonstrator Suit (Mark III) for use as a design tool. This suit was chosen because the hip joint is made of rigid sections that can be modeled with current technology. The results of this test will pave the way for further model development and tests to evaluate all rigid sections of the Mark III suit and will eventually be enhanced with the flexible cloth sections.

The study commenced by examining general changes in mobility performance due to hip bearing modifications (e.g. individual bearings were fixed). Human performance data from the Mark III was examined with the nominal and modified bearing configurations. The Mark III hip bearing model was then created, tested, and validated with the suited human performance data.

2 METHODS

2.1 Suited Human Subject Performance Testing

Four male subjects participated as test subjects for this evaluation. The test subjects were selected for similar hip and leg anthropometry in an effort to reduce human variation in the data. Table 1 shows how the subject's anthropometry compared to the rest of the astronaut population (NASA, 2009). Suited human subjects performed isolated motions of maximal hip flexion and hip abduction while being recorded with motion capture equipment. There was some difficulty with matching the motion of the suit to the pure definition of the hip angles as the mechanics of the suit forced the subjects into mixed flexion/abduction while "flexing" and mixed abduction/external rotation when "abducting" as the leg follows the hip join bearings' arcs of movement. For simplicity's sake, these compound motions were defined as flexion and abduction.

Table 1. Distribution of the subjects' average among the astronaut population.

Anthropometry	Stature	Hip Breadth	Thigh Circumference
Average (cm)	179.4	35.8	63.5
St. Dev.	5.2	1.1	3.4
Population Percentile	52.6	67.4	74.5

Retro-reflective markers were placed on key landmarks of the suit (see figure 1). Data was processed with a custom-made inverse-kinematic model and processed with a fourth order, zero-lag, high-pass Butterworth filter with a cut off frequency of 6 Hz. Definitions, reference frames, and reference planes commonly used were prescribed by the International Society of Biomechanics (Wu and Cavanagh, 1995). The motion capture data was processed using standard motion capture analysis techniques. Joint angles computed for the hip joint used a flexion, rotation, adduction Euler angle sequence.

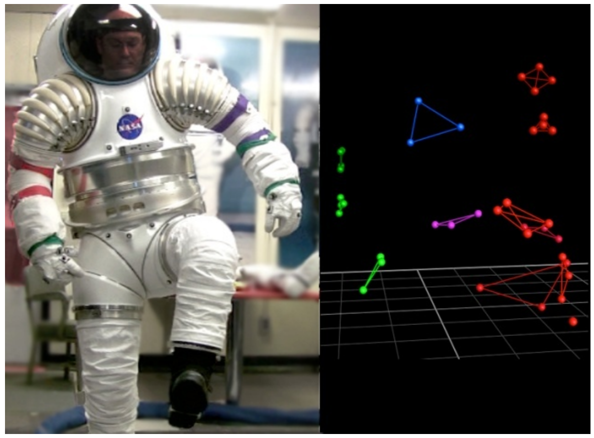

Figure 1 Motion capture of a subject in hip flexion (left), and the resulting 3D motion data (right).

2.2 Suit Model Development

A 3D solid model of the suit and a representative human manikin were created in SolidWorks (Dassault Systèmes, Vélizy-Villacoublay, France) (see figure 2). The rigid sections of the suit models were reverse-engineered from the Mark III brief and hip bearings. The measurements taken were accurate to within ± 1 mm. The model includes the upper hip bearing (UHB), mid-hip bearing (MHB), lower hip bearing (LHB), and the rolling convolute joint (RCJ) at the mid-thigh.

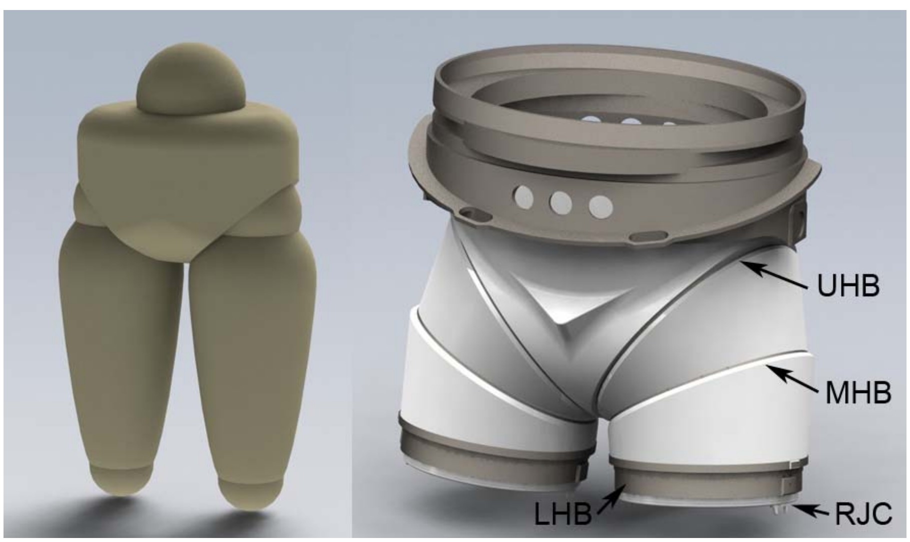

Figure 2 Illustration of a 3D solid model of a subject's pelvis and thigh (left), and the Mark III Technology Demonstrator Suit brief and hip bearing model (right).

The partial human manikin was scalable with respect to specific anthropometric measures for the pelvis and thigh (see figure 2). Only the hip breadth, thigh circumference, and femur length were used as scaling dimensions for this study. Subject measurements were taken either with an anthropometer or tape measure or extracted from 3D scans.

The SolidWorks platform allows for the creation of 3D assemblies of multiple solid parts that have some degrees of freedom constrained to each other through geometry, while remaining fully articulating in the other degrees of freedom. SolidWorks also allows for exact measurements to be made between points, lines, planes, or surfaces while in any configuration.

The manikin was aligned so that the sagittal plane of the pelvis was co-planar with the sagittal plane of the brief. The x-axis of the hip socket is fixed coincidentally with the UHB centroid. Keeping the hip in a fixed location between conditions was necessary since the true location of the hip would be dependent on a myriad of human-related variables and was the best option outside of allowing the hip to free-float within the brief. Co-locating the hip socket axis and the UHB centroid also provided the largest possible ROM for all of the test conditions in a fixed hip state.

Maximum flexion was determined for each configuration by determining when the knee joint center of the manikin was at its most anterior position (see figure 3). This was done because of the non-planar and circular paths of the bearings. The most anterior position measurement allowed for a consistent measurement to be taken between conditions and still achieved a large flexion angle. Once the suit was taken to the end range, joint angles and bearing rotations were measured within the SolidWorks software.

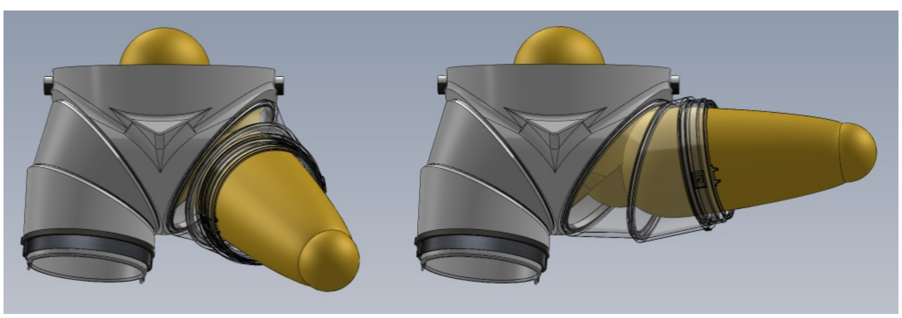

Figure 3 Illustration of the Mark III model with a subject manikin in the maximum flexion (left) and abduction (right) positions for the nominal condition.

Maximum abduction was determined for each configuration by putting the manikin knee joint center at its most superior and lateral position (see figure 3). This orientation of the leg was also chosen because of the non-planar and circular paths of the bearings and the inability to move in true abduction. The most superior and lateral position measurement allowed for a consistent measurement to be taken between conditions, achieve the largest abduction angle, and provide a simple method of comparing the bearing model to the human subject data.

3 RESULTS AND DISCUSSION

3.1 Suited Human Performance and Suit Model Data

Charts 4 and 5 illustrate the differences between the model data and the human subject data for the hip joint angles. The charts show the mean and span of the maximum angle ranges across all four subjects for flexion and abduction against the bearing model's estimated maximum angles. The hip joint angles were measured from the thigh relative to the pelvis. The angles are reported as positive if in flexion or abduction. The suit model predicted an approximate 60% reduction in maximum flexion and abduction with the UHB locked and an approximate 25% reduction with the LHB locked, but only a negligible change with the MHB locked in comparison to the unlocked state.

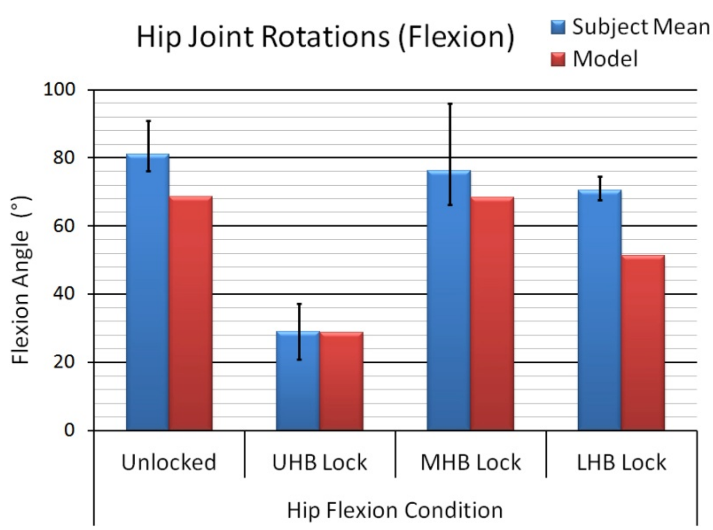

Figure 4 A comparison of the maximum hip flexion mean (blue) with an error bar of the highest maximum and lowest maximum across subjects as compared to the model (red).

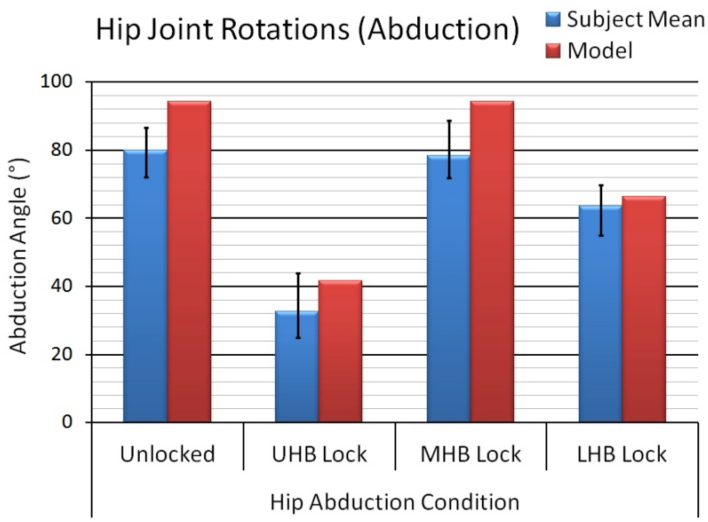

Figure 5 A comparison of the maximum hip abduction mean (blue) with an error bar of the highest maximum and lowest maximum across subjects as compared to the model (red).

Although not all of the model predictions fit within the range of the peak angles of the human tests, the performance trends are kept. The error between the model prediction and the subject data range was < 10%, except for the LHB locked condition in flexion (figure 4), which had a 24% error.

There were some physical differences between the 3D solid model of the joint bearings and the human test subject environment. For this study the manikin model was locked into a specific orientation/location within the brief and hip flexion and abduction definitions were standardized between conditions, whereas the human subjects were allowed to move freely within the brief and choose for themselves where their maximum flexion and abduction angles were. Similarly, there was a fair amount of slop in the suit's fit around the knee and lower thigh, allowing for greater motion, as seen in the LHB locked condition. Other factors included the lack of dynamic elements in the model, such as mass, gravity, resistance, suit-human contacts, or joint moment restrictions.

3.2 Suit Model Visualization

Mobility visualizations were created to show the generally unused regions of motion that the hip bearing of the Mark III allows for. Figure 6 is an illustration of the hip mobility in the Mark III compared to unsuited hip motion. Each shape represents the possible locations of the knee joint in 3D, the blue disk-like area is the maximum allowable motion of the Mark III in the nominal condition, and the green is unsuited hip motion for common tasks (walking, kneeling, climbing, etc.). Functional hip motion is taken from published walking data (Gage, DeLuca, and Renshaw, 1995) and previous NASA functional mobility tests (England, Benson, and Rajulu, 2010). The general area of unsuited hip motion not accounted for by the Mark III hip joint is shown as the green volume not overlapped by the blue. Approximately 60% of the unsuited hip motion area would have been unreachable by someone in a Mark III suit trying to move in the exact same way. The inverse of the previous statement is also represented visually where only a fraction of the allowable mobility of the Mark III would be used to perform common tasks without compensating with other joint motion (i.e. waist and leg rotation).

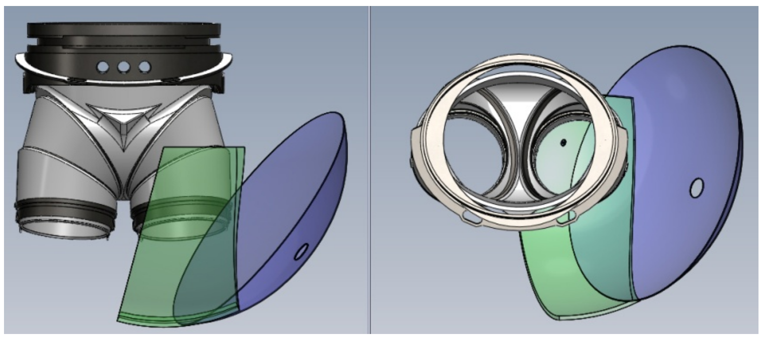

Figure 6 Mark III hip mobility (blue shape) vs. estimated human functional hip use (green shape).

The mobility of each bearing configuration can also be visualized and quantified into an area as was shown in figure 6 to compare configuration changes and the impact each bearing has on the overall mobility. For example, Figure 7 illustrates the model's capability to represent all possible locations of the knee joint center in 3D space (blue disk-like area) when the UHB was locked. For this condition the available range of motion was greatly reduced and was limited to a ring shape. The motion volume was created by superimposing the allowed motion for each of the bearing segments. Comparing the UHB locked condition to the nominal condition revealed a reduction of 96% in total movement area of the knee joint center.

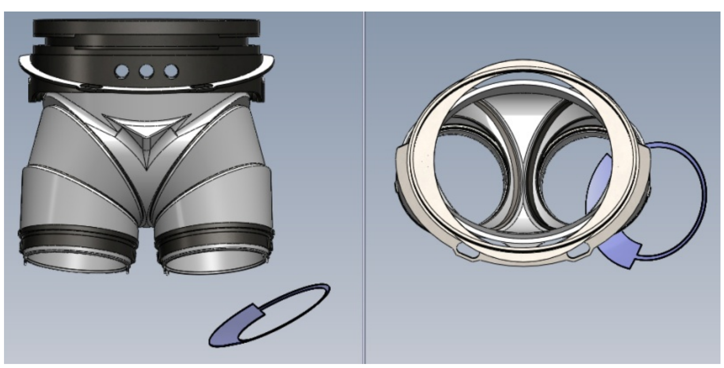

Figure 7 Visualization of the allowable mobility of the knee joint center with the UHB locked.

4 CONCLUSIONS

The bearing model results demonstrate that modeling the Mark III brief and hip bearing sections for use as a performance design tool was feasible and useful. Although not all of the model predictions fit within the range of the peak angles of the human tests, they are representative to a reasonable degree considering the testing limitations. This was especially true for the conditions that limited the performance, such as with the UHB and LHB locked conditions. It is reasonable to state that such models of the hard segments and bearings of the suit are feasible and useful in studying and analyzing the behavioral characteristics of these joint bearings. Models cannot replace human-in-the-loop performance and verification tests, but may offer a huge benefit in conjunction with human testing to improve efficiency within the human-centered design process and for making sure that later stage designs adhere to requirements. The benefits of a suit joint model offers an added advantage to traditional suit design by allowing designers to visualize performance changes, instead of theorizing outcomes and building prototypes to test those theories out. It also gives designers the ability to think outside the box and exhaust design possibilities without additional resources, thereby getting to the optimal bearing designs much quicker.

This model will form the basis for the evolution of a full suit and human dynamics model, capable of calculating workloads, efficiencies, and injury predictions. This model and analysis are initial steps in the development of a more complex virtual design tool that will aid suit developers in creating the next generation space suits with increased efficiency, reliability, and performance. Advances in software capabilities and computer processing power have enabled us to efficiently create dynamic bearing models that could be used to predict suit-human contact forces and internal suit resistances. A biomechanical model of this magnitude could eventually lead to predict injury potentials for planned tasks, suit architectures, hardware designs, or contingency situations.

ACKNOWLEDGMENTS

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REFERENCES

Cutkosky, M.R., R.S. Engelmore, R.E. Fikes, et al. 1993. PACT: an experiment in integrating concurrent engineering systems. *IEEE Computer*, 26: 28-37

England, S.A., E.A. Benson, and S.L. Rajulu. 2010. Functional Mobility Testing: Quantification of Functionally Utilized Mobility among Unsuited and Suited Subjects. NASA/TP-2010-216122.

Gage, J.R., P.A. DeLuca, and T.S. Renshaw. 1995. Gait analysis: principle and applications with emphasis on its use in cerebral palsy. *J Bone Joint Surg Am*, 45: 1607-1623.

NASA. 2009. Constellation Program Human-Systems Integration Requirements. CxP 70024, Rev D.

Wu, G. and P.R. Cavanagh. 1995. ISB recommendations for standardization in the reporting of kinematic data. *J Biomech*, 28: 1257-1261.