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Modeling Space Suit Mobility: Applications to Design and Operations

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ABSTRACT

Computer simulation of extravehicular activity (EVA) is increasingly being used in planning and training for EVA. A space suit model is an important, but often overlooked, component of an EVA simulation. Because of the inherent difficulties in collecting angle and torque data for space suit joints in realistic conditions, little data exists on the torques that a space suit's wearer must provide in order to move in the space suit. A joint angle and torque database was compiled on the Extravehicular Maneuvering Unit (EMU), with a novel measurement technique that used both human test subjects and an instrumented robot. Using data collected in the experiment, a hysteresis modeling technique was used to predict EMU joint torques from joint angular positions. The hysteresis model was then applied to EVA operations by mapping out the reach and work envelopes for the EMU.

INTRODUCTION

The capabilities of EVA astronauts to do useful work outside of their spacecraft have steadily progressed, since the first EVAs were done in 1965. Likewise, our understanding of EVA astronauts' capabilities and limitations have also progressed through inflight experience, experimentation in neutral buoyancy and parabolic flight, and engineering tests of space suits and EVA tools. Computer models and dynamic simulation are the most recent tools for analyzing EVA capabilities.

Computer simulation of EVA has several advantages over physical simulations, including the ability to accurately reproduce forces and displacements in six degrees of freedom and the absence of inherent time and workspace limitations. Computerized analysis can reduce costs of planning and training by replacing some expensive physical simulator time with less labor-intensive computer simulation, allows for rapid reconfiguration of a simulated workspace configuration, and can accommodate repetitive tasks. Computer simulation also aids in future space suit design by allowing new space suit or component designs to be evaluated without the expense of constructing and certifying prototypes for human testing. While dynamic simulation is not currently used for EVA planning, it has been used for post-flight analyses [1, 2]. Other computer-based modeling and analysis techniques are used in pre-flight evaluations of EVA tasks and worksites [3, 4].

An important shortcoming of current EVA models is that they lack an accurate representation of the torques that are required to bend the joints of the space suit. The shuttle EMU, like all pressurized space suits, restricts joint motion to specific axes and ranges and has a tendency to spring back to its neutral position when the wearer relaxes. The torques that are required to bend the space suit joints limit suited strength, induce fatigue, alter mass-handling dynamics, and limit the volume in which a suited person can comfortably work.

A simulation study of large mass handling in EVA demonstrated the importance of space suit-induced torques in drawing conclusions from EVA task analyses. In this study, a simulated EVA crewmember moved the 1200 kg Spartan astronomy payload about a circular trajectory. The body configurations and joint torques that were required to move the large mass were calculated, first without a space suit, then with a simple space suit model. Addition of the space suit model to the simulation dramatically changed the simulated crewmember's body position and the torques required to move the payload. Although the simulation study used a simple space suit model that was based on a small data set, the differences in the results with and without the space suit model serve to illustrate the importance of an accurate space suit model for realistic simulation results[5, 6].

Researchers attempting to develop models of the torque-angle characteristics of the space suit face important limitations. Numerous methods exist for measuring the angular positions of joints; however, it is impossible to directly measure joint torques in a human subject wearing a space suit, without interfering with the subject's motion or using invasive instrumentation. Several investigators have measured the torques required to bend space suit joints, in most cases with pressurized but empty space suits [7, 8, 9] and in one case, by comparing suited and unsuited strength with human subjects[10]. Table 1 shows torque values that were reported where these investigators' data sets overlapped. The torque values that were measured when a person was wearing the suit were generally higher than those measured with an empty suit, as shown both in Table 1 and Figure 2. These experimental results hint that empty-suit torque measurements may underestimate the torques required to bend the space suit's joints, possibly because the empty-suit torque measurements do not account for contact between the space suit and the wearer's body.

Table 1: Space suit joint torques

Study	Dionne [7]	Abramov et al [9]	Morgan et al [10]
Methods	EMU Empty suit	Orlan-DMA, 4.3 psi (30 kPa) Empty suit	EMU Human Subjects
Knee, 72 degrees	3.2 Nm	6.0 Nm	8.1 Nm
Elbow, 80 degrees	2.0 Nm	2.2 Nm	3.4 Nm

A space suit torque model can be used as part of a work envelope analysis based on inverse kinematics. In planning EVAs and designing EVA work areas, it is crucial to determine in advance whether a crew member can reach a work site from the available restraints. The work volume currently used for these analyses [3, 4] is a cylindrical volume centered on the body centerline, which was determined in human tests and published in "Space Shuttle Systems Payload Accommodations" NSTS 07700 [11]. The NSTS 07700 work envelope is not resizable for different sized individuals and does not indicate which areas inside the work envelope are easier to reach.

This research effort had three objectives:

- Compile a torque-angle database on the EMU joints, using realistic motions.
- Develop a model relating joint torques to joint angles.
- Apply the space suit torque model to EVA operations in a work envelope analysis.

EXPERIMENT

The objective of the experimental phase was to obtain a quantitative database of joint angles and torques required to move the EMU joints, under realistic conditions. In order to accomplish this, human test subjects carried out arm and leg motions both wearing the space suit and not wearing the space suit, supplying realistic joint angle trajectories for each of the motions. The joint angle trajectories produced by the human subjects were then used as commands for the robot, so that the robot imitated the humans' motions while torques were measured at each of the robot's joints. The torques required for the robot to reproduce the human subjects' motions were measured both with the space suit installed on the robot and without the space suit. The difference between suited and unsuited torques measured by the robot indicates the torques required to bend the space suit joints.

HUMAN TESTING - Suited and unsuited human subjects performed a series of arm and leg motions to supply realistic joint angle trajectories. Four male subjects participated in the experiment; two of the subjects were experienced in 1-g testing of the EMU. The experiment was approved by the Massachusetts Institute of Technology's Committee on the Use of Humans as Experimental Subjects and informed consent was obtained from each subject prior to each experimental session.

The space suit used in these experiments was a Class III EMU supplied by Hamilton Sundstrand. A size large hard upper torso (HUT) was used, and a volumetric mockup was substituted for the portable life support system (PLSS), resulting in an overall weight for the space suit and PLSS mockup of 46.4 kg (102 lb).

Twenty motions were used for human and robot data collection. The motions, listed in Table 2, included 11 simple motions that isolated each degree of freedom and 9 more complex, free-form motions, which included reaching over the head, across the body and to an object 50 cm above the floor. Free-form motions were included for two reasons: to evaluate the effects of multi-joint motions and to compare the subjects' choices of arm and leg positions between suited and unsuited conditions Subjects also walked on a treadmill and traversed a 12 cm high step, pictured in Figure 1A. Trial ordering was randomized, with simple motions presented first, followed by free-form motions. Subjects performed the arm and leg motions in two sessions. The first session was conducted without the space suit and the second session was done with subjects wearing the space suit, one week later. Kinematic data was collected on the subjects' right arm and leg, using a Multitrax optical motion capture system (Adaptive Optics Associates, Cambridge, MA).

Angles between adjacent arm and leg segments were calculated from the Cartesian positions of reflective markers obtained from the video motion capture system. The error in locating a marker which is visible to the video cameras is less than one marker diameter, or 1 cm. Based on the arrangement and spacing of markers on the test subjects, a 1 cm error in locating markers translates into maximum errors of approximately 2 deg - 5 deg in elbow, shoulder or knee joint angles.

A B C

Figure 1. A. Suited test subject traversing 12 cm step. B. Robotic Space Suit Tester. C. RSST with EMU installed

Table 2: Arm and leg motions used in experiment

Simple Motions	Free-form Motions
Shoulder flexion	Arm swing forward-backward
Shoulder abduction	Arm swing side to side
Humerus rotation	Leg swing forward-backward
Elbow flexion	Leg swing side to side
Hip flexion	Overhead reach
Hip abduction	Cross-body reach
Thigh rotation	Low reach
Knee flexion	Locomotion over 12 cm step
Ankle rotation	Locomotion on treadmill
Ankle flexion	
Ankle inversion	

ROBOT DATA ACQUISITION - The Robotic Space Suit Tester (RSST) is an anthropomorphic robot built for NASA space suit mobility research by Sarcos, Inc. (Salt Lake City, UT). The RSST, which is shown in Figure 1B, has 12 hydraulically actuated joints on the right arm and leg and 12 posable joints on the left arm and leg. At each actuated joint, potentiometers measure joint deflection and strain gauge load cells measure torque. The robot can follow pre-programmed trajectories, simultaneously recording joint positions and torques.

Joint angle data from the human subjects was first used to drive the unsuited robot to record baseline torque values caused by the weight of the robot's limbs. The EMU used in the human subjects phase of the experiment was then installed on the robot, and pressurized to 30 kPa (4.3 psi), as shown in Figure 1C. The suited robot was then driven with the human joint angle data and the torques required to accomplish the motions were recorded. To remove the contributions of the robot's weight from the torque data acquired with the space suit on the robot, the unsuited torque data was subtracted from the suited torque data. Torques due to the weight of the space suit were calculated and subtracted based on the known mass properties of the EMU and the position of the space suit segments relative to the robot's joints. The result was a consistent set of joint angle and space-suit induced joint torque data. Figure 2 shows examples of suit induced torques for the elbow, knee, shoulder and hip joints for both data collected in this experiment and another published data set [7].

Accuracy of the data obtained from the robot is affected both by torque measurement errors and errors in positioning the robot. Random error in torque measurements is very low, approximately 0.1 Nm. An assessment of the load cells' calibration indicated that bias errors were less than 4% for all joints. Root mean square errors in joint positioning ranged from 0.5 degrees to 2.5 degrees, depending on the joint, due to inadequate tuning of the robot's servo gains.

MODELING

The torque and angle data obtained in the human and robot experiments were used to model the torque-angle characteristics of the EMU joints.

Hysteresis is a common characteristic of fabric structures. When fabric is loaded, the individual yarns both elongate and slide over each other, resulting in load-extension curves characterized by the yarn compliance and the friction between yarns[12]. Torque-angle measurements made on both the EMU and prototype space suit joints in previous studies, as well as the data collected in the current study, indicate that the torque-angle relationship for a fabric space suit joint is hysteretic. A Preisach hysteresis model was used to model joint torques as a function of joint angle [13].

The Preisach model reproduces a hysteresis curve by summing contributions from the simplest possible hysteresis transducers.The primitive hysteresis transducer, $\hat{\gamma}(\alpha, \beta)$, is shown in Figure 3A. For ascending inputs, the output follows the path abcde; for descending inputs, the output follows edfba. The two parameters that may be set are the ascending and descending switching values, a and b. The output of the transducer is always either -1 or +1.To construct more complicated hysteresis transducers with continuous, non-unity outputs, such as the one shown in Figure 3B, the Preisach model uses a weighted sum of simple hysteresis operators. The weighting function $\mu(\alpha,\beta)$ is defined as a function of the combination of upward and downward switching values, α,β, of the hysteresis transducer. Construction of the output of the composite hysteresis transducer is done by integrating the individual $\hat{\gamma}_{\alpha,\beta}$ values, as shown in Equation 1 [11].

$$f(t) = \int_{-\alpha_0}^{\alpha_0} \int_{\beta}^{\alpha_0} \mu(\alpha, \beta)\hat{\gamma}_{\alpha, \beta}u(t)d\alpha d\beta \qquad \text{Eq. 1}$$

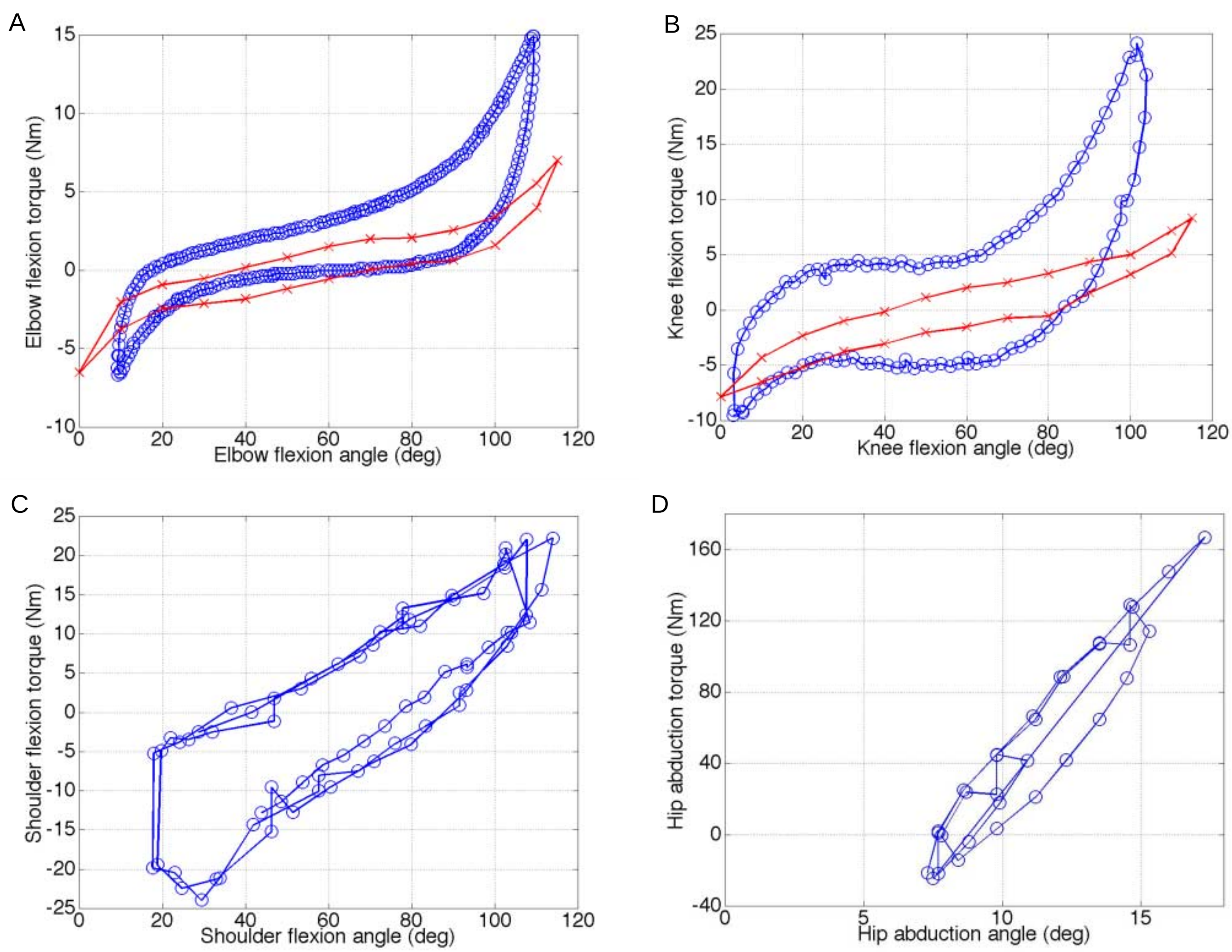

Figure 2. Torque plotted vs. angle. Circles indicate data from the present study and the x's in A and B indicate data from Ref. 7. A. Elbow flexion B. Knee flexion C. Shoulder flexion D. Hip abduction

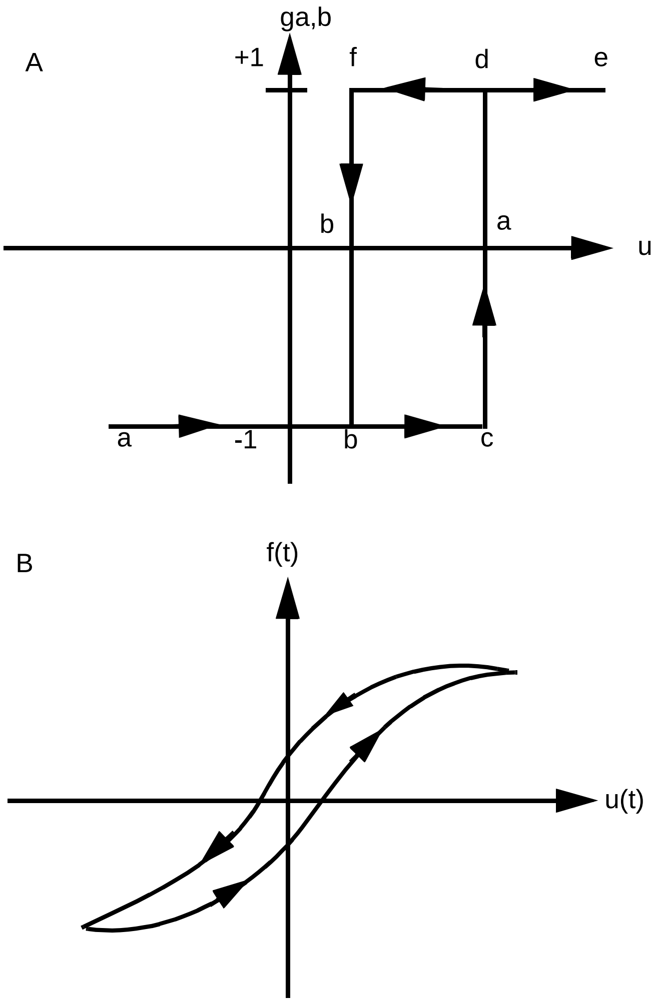

Figure 3. A. Simplest hysteresis operator. B. Input-output curve of a more complicated hysteresis transducer.

The weighting function $\mu(\alpha,\beta)$ characterizes the hysteretic system. Fitting the Preisach hysteresis model to a set of data involves determining the weighting function $\mu(\alpha,\beta)$ that reproduces the hysteresis curves in the data set. For mechanical systems, this is accomplished by determining the system's output for transitions between many different minima and maxima. Since human subjects produced the realistic joint trajectories that served as the robot's inputs, the conventional approach was not practical. A new method was developed to find the weighting function $\mu(\alpha,\beta)$ that would reproduce the space suit's torque-angle curves, based on the data obtained in the experiments. The weighting function $\mu(\alpha,\beta)$ was determined that provided the best fit to the outermost hysteresis curves, then the Preisach model concept was used to interpolate between the outer curves for transitions between arbitrary minima and maxima. Results of a hysteresis model fit for the elbow flexion joint are shown in Figure 4. In this case, the model predicts elbow joint torque over a 14 deg-99 deg range of elbow flexion angle, with a root mean square error of 1.4 Nm.

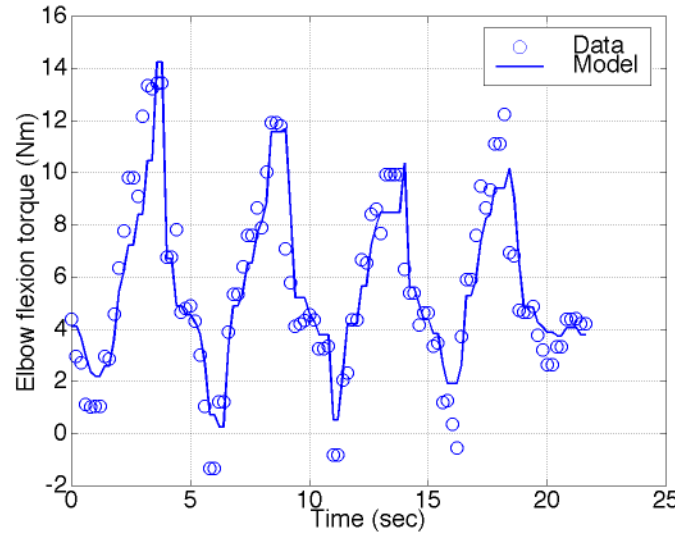

Figure 4. Hysteresis model fit for elbow joint.

WORK ENVELOPE FOR EVA OPERATIONS

The work envelope is the volume in space in which a person can comfortably work. The EVA work envelope analysis tests proposed hand locations and includes them in the work envelope if they are visible and can be reached by a space-suited person with either hand without requiring excessive torques at any joint.

Visibility of a proposed hand location is determined first based on the field of view from the EMU helmet published in NSTS 07700 [11]. Points that fall within the field of view are then evaluated to determine if they are reachable without excessive joint torques.

Torques required to place the hand at a point in space are determined by first using inverse kinematics to calculate the angles of the four arm joints needed to place the hand at the target, then using the space suit torque model to determine the torques required to maintain the required joint positions.

Inverse kinematic analysis of the arm was done using a geometric method for an arm with four degree of freedom: shoulder flexion, shoulder abduction, shoulder twist, and elbow flexion [14]. The wrist joint was not considered, because it was not possible to obtain wrist joint torque data in the experiment. Since three coordinates of hand position determine four joint angles, the system is underdetermined and there are multiple arm configurations that result in the same hand position.

The torques required at each of the four joints to maintain the proposed hand position were calculated from the space suit model. For each arm configuration, a difficulty metric was calculated, based on the ratio of required

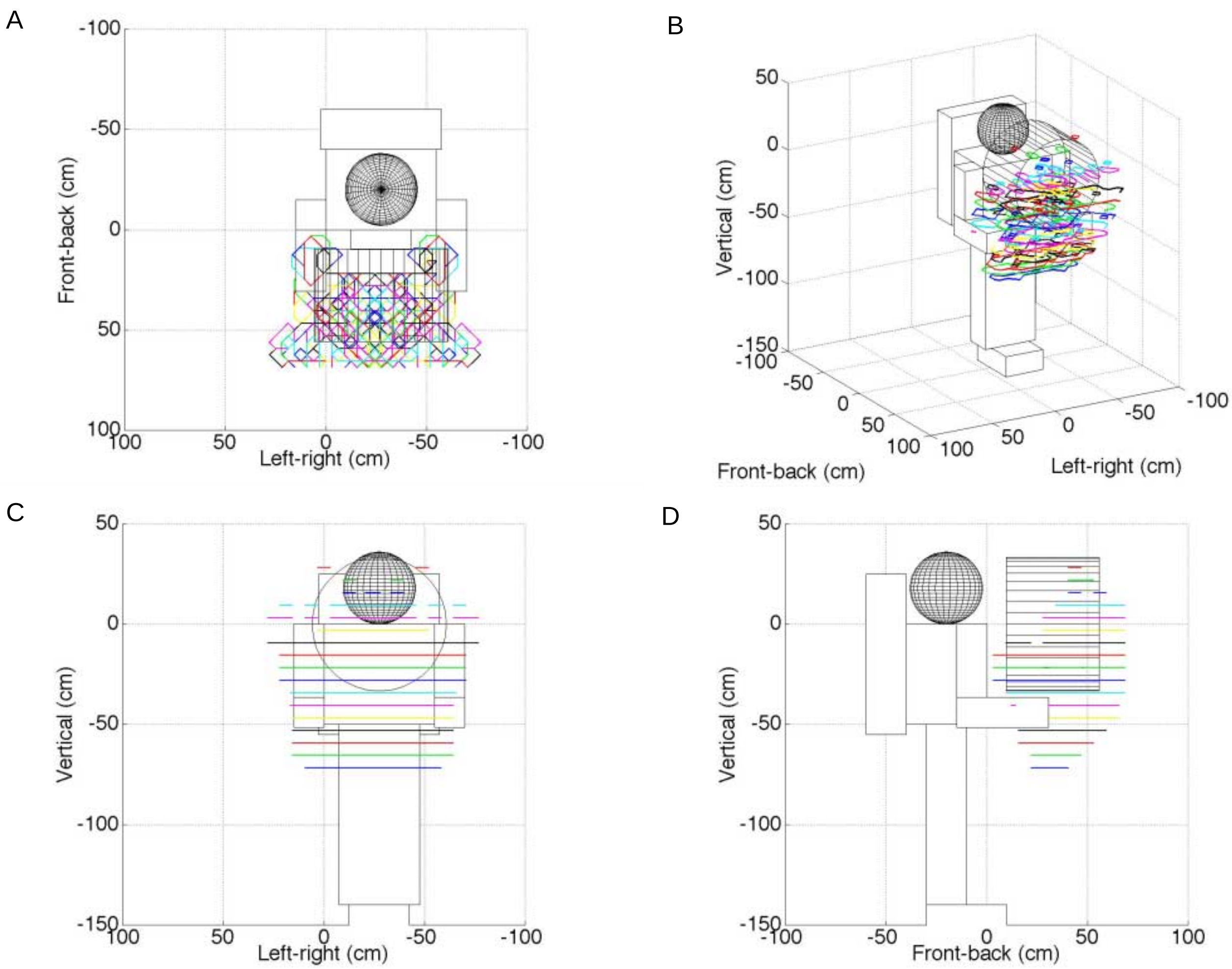

Figure 5. One handed work envelope for 50th percentile male. The cylinder is the one-handed work envelope from NSTS 07700, shown for comparison.

torque to available torque at each joint, as shown in Equation 2.

$$\text{Difficulty metric} = \sum^{\text{4 Joints}} \frac{\text{Required torque}}{\text{Available torque}} \qquad \text{Eq. 2}$$

If the difficulty metric for any joint exceeds 1, the proposed hand position is considered to be outside of the workspace.

The torque limits that were defined for each joint represent 15% of the maximum isometric torque [15] possible for that joint. The 15% limit was chosen to correspond to a torque value that a person can maintain for several minutes [16].

The one-handed work envelope using anthropometric data for a 50th percentile male is shown in Figure 4, with the NSTS 07700 [11] cylindrical one-handed work envelope shown for comparison.

DISCUSSION AND CONCLUSIONS

EMU TORQUE-ANGLE DATABASE - Figure 2 shows torques plotted vs. angles for the elbow flexion, knee flexion, shoulder flexion and hip flexion joints. The amplitudes of the torques vary greatly for different joints, with the hip abduction joint requiring torques several order of magnitude higher than those required to move the shoulder, elbow and knee joints. The torque-angle curves also show hysteresis; the direction of motion affects the torque required to move the joint. Comparing the torques measured in this experiment to those reported by Dionne[7] and Menendez[8], the current torque measurements are higher in magnitude, although the general hysteretic shape of the curves approximately agree. The slopes of the torque-angle curves are higher near the extremes of the angle range for the data recorded in this experiment, possibly due to contact effects between the space suit and the robot. Torque magnitudes do, however, seem to agree with Morgan et al's [10] measurements from Table 1, although the comparison is very limited.

HYSTERESIS MODEL - The hysteresis model allows the torque-angle database to be reduced to a more compact set of coefficients that can be used to calculate the torques required to perform an arbitrary joint motion. An important limitation of the hysteresis modeling technique used here is that it does not incorporate any physical processes, and consequently, it does not contribute insights for designing space suit joints with better mobility characteristics.

WORK ENVELOPE ANALYSIS - The work envelope analysis applies the EMU database and hysteresis model to EVA operations. The analysis assumes that a point is within the work envelope if it is visible and can be reached by either hand, without requiring excessive torques at any joint. The work envelope analysis method can be resized to accommodate individuals or populations of different sizes and strength, within the limits of the space suit configuration that was tested. Incorporating joint torques in the work envelope analysis enables comparisons of the difficulty of reaching different points that fall within the work space.

The wrist joint was not included in the work envelope analysis, because it was not possible to measure space-suit induced torques at the wrist joints with the RSST. Considering only the four joints at the shoulder and elbow captures the essential features of the work envelope for hand positioning, while minimizing the kinematic redundancy of the modeled arm. Reducing kinematic redundancy makes computation more efficient and avoids arbitrary choices of arm configurations that may not coincide with realistic motions. If a work envelope analysis were done specifying both hand position and orientation, it would be necessary to include the wrist joints. A more detailed work envelope analysis, considering hand orientation in addition to position, would be an interesting area for future work.

The work envelope shown in Figure 5 has a complicated shape. Its boundaries are determined by visibility, arm length, and joint angle limits. Effects of visibility can be seen in Figure 5A, where an area close to the body is excluded from the envelope. Arm length sets the maximum distance from the body that a person can reach, shown in Figure 5D as the forward boundary of the work envelope. Finally, joint angle limits set the inner boundary and left and right limits of the work envelope, as can be seen in Figure 5B and Figure 5C.

Comparisons between the one-handed work envelope obtained here and the one-handed work envelope published in NSTS 07700 indicate that there are some areas inside the NSTS 07700 work envelope low, near the center, and close to the body that are not visible and areas high near the body center that are difficult to reach. The work envelope analysis predicts that there are additional areas below the NSTS 07700 work envelope where it may be possible to work.

In conclusion, this research compiled a database of torques required to bend the joints of the EMU space suit using human subjects and an instrumented robot to obtain torque measurements in realistic motions. A mathematical model was developed to predict joint torques from the joint angle history. The model was applied to EVA operations by a work envelope analysis predicting the boundaries in which a space-suited person could perform one-handed work.

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