SAE TECHNICAL PAPER SERIES

2000-01-2257

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The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL

30th International Conference on Environmental Systems
Toulouse, France
July 10-13, 2000

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A.Tel: (724) 776-4841 Fax: (724) 776-5760

ISSN 0148-7191

Printed in USA

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MODELING THE EXTRAVEHICULAR MOBILITY UNIT (EMU) SPACE SUIT: PHYSIOLOGICAL IMPLICATIONS FOR EXTRAVEHICULAR ACTIVITY (EVA)

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ABSTRACT

Extravehicular activity (EVA) is investigated through experiments testing an actual extravehicular mobility unit (EMU) performing several EVA tasks in the laboratory, and a dynamic model of the EMU space suit is developed. Building directly on earlier work in EVA simulation, the space suit model was created from mass, inertia, and performance data to augment the unsuited 12-segment human model used in previous studies. A modified Preisach model was used to mathematically describe the hysteretic torque characteristics of joints in a pressurized space suit, and implemented numerically based on observed suit parameters. Computational simulations, based loosely on a 1995 EVA involving manipulation of the Spartan astrophysics payload, were performed to observe the effect of suit constraints on simulated astronaut performance. Results show that the shoulder joint work required for a suited EVA crewmember to move the payload while in an inefficient posture was an order of magnitude greater than it was in the unsuited condition. Moving to a posture more accommodating to the suit's neutral position, the simulated astronaut completed the task using only 23% of the work required in an inefficient posture. However, the ankle joint was forced to use its long lever arm to manipulate the payload, resulting in ankle work 3 times greater than in the unsuited condition. These results agree with anecdotal evidence of post-EVA ankle fatigue, and suggest promise for both the space suit model and the simulation technique. Current experimental research that complements the analytical EMU dynamic modeling is targeted towards gathering simultaneous joint angle and torque data from actual space suit tests. Since it is not possible to measure joint torques in human subjects, NASA's robotic space suit tester (RSST) is used for torque measurements. The database of joint angles and torques caused by the space suit provides a verification and enhancement to the space suit dynamic model, including more joints with higher fidelity for complex motions.

INTRODUCTION

Numerous studies have attempted to characterize the particular workspace to which a suited astronaut is restricted [1]. These dimensions aid EVA planners in describing feasible EVA tasks, assuring that the reach envelope required for a given task will not exceed the reach envelope available to the astronaut. Computer-aided design facilities have already incorporated similar data into EVA planning software [2, 3]. Workspace definitions, however, do not take into account the appreciable dynamic effects that a 200-lb space suit with significant joint torques will have on astronaut strength and mobility during an EVA task. Data is only beginning to appear with regard to available suited strength, [4, 5, 6] and thus make its way into the EVA design process. Even if armed with this data, EVA designers will only be able to make rough estimates of strength needed vs. strength available for a given task. These static measurements of performance do not allow for the direct comparison of tasks that have been choreographed in a particular way, or of the astronaut effort required to execute each task in terms of total work performed, distribution of work among the various muscle groups, and issues involving the gradual onset of fatigue.

Computer simulation of EVA tasks provides one solution to these questions, allowing designers to observe how suit effects may influence overall EVA performance. A dynamic suit model can follow astronaut movement through a simulated EVA task and apply appropriate inertial and suit-generated loads to crewmember limbs during the simulation. The resulting time histories of position, velocity, and acceleration for various body segments then generate profiles for energy expenditure and work performed over the course of the task. Problem areas can be identified, and choreography refined to account for predicted complications.

This method also provides a six degrees-of-freedom (dof) arena in which the simulated EVA crewmember can work, allowing for unrestrained multibody interactions in a microgravity environment. Although physical simulators such as Neutral Buoyancy Laboratory (NBL) are excellent for both training and EVA choreography, these and other gravity-bound devices have inherent limitations; it has been shown that quantitative pre-flight analysis of EVA tasks in six dof can help to reveal the sometimes quite subtle differences that accompany work in an EVA setting [7].

METHODS

A data-driven dynamic model of the EMU space suit was constructed from three key suit parameters: mass, inertia, and suit-generated torques. Mass data for the individual EMU components, including the PLSS, were obtained from Hamilton Standard. [8] Various moments of inertia were computed from suit dimensions, [9] and the basic mass model was recorded in a system description file for the SD/FAST multibody dynamics software package.[10] SD/FAST was then used to formulate the dynamic equations of motion for a 12-segment human model [11], incorporating the additional space suit segments.

To verify the analytical modeling effort, actual spacesuit tests were performed in the 1 G laboratory environment with the robotic space suit tester (RSST). The RSST is an anthropomorphic robot with 12 actuated and instrumented joints in its right arm and leg. The human-sized robot offers precise three-dimensional motion and joint torque measurements. The analytical modeling insights are verified through experimental tests with suited human subjects and a suited robot. An EMU was installed on the RSST and pressurized, and the robot is commanded to follow human subject motions. Data was collected for unsuited human motions, suited human motions, commanded robotic motions, and commanded suited robotic motions.

SUIT-IMPOSED TORQUES - The most profound effect of the EMU on astronaut performance involves the imposed torques, or "springback forces," in the joints; these forces are generated when the suit fails to maintain a constant volume during movement, and the astronaut does work to change suit volume and position. Also, the multi-layer soft shell construction of the suit behaves much like a giant winter coat: as the limbs move back and forth between joint limits, the suit fabric tends to bunch up, and eventually the sheer quantity of material compressed into a small volume creates a firm limit on the maximum flexibility of a joint.

Space suit design engineers, of course, attempt to minimize these effects in order to maximize suit flexibility and astronaut mobility. [12, 13] For the most part, suit designers have succeeded; joint restraints are quite effective in maintaining a nearly constant joint volume through the most frequently used areas of an astronaut's workspace, and innovative designs such as flat-patterned mobility joints allow easy flexing of joints without substantial twisting, bunching, or stretching of thermal micrometeoroid garment (TMG) material.

The effects being modeled, then, are not the major suit forces associated with early space suit designs which lacked these improvements. [14] Rather, we attempt to model the EMU's deviation from a "perfect" suit, one which would exert no forces to counteract astronaut movement. In practice, subtle changes in the orientation of joint restraints during a particular motion can lead to minute variations in the restraint forces applied to EMU joints. Additionally, TMG fabric will be thick and bulky regardless of joint design innovation, and it will contribute some small counter-torque to astronaut movement. These variations lead to slightly varying joint volumes during particular sequences of arm and leg motion, and increasing fabric bunching toward the joint limits; the result is the characteristic joint angle versus suit torque curve of Figure 1, obtained from torque measurements of a pressurized suit elbow over its range of motion. [6] This modeling effort focused on developing a dynamic model of the EMU from existing suit data, which presumably represents some combination of the effects that various suit imperfections have on suit performance. Although mass and inertial properties complete the model, these springback torques represent the critical element for assessing detriments to human performance in the EMU. The modeling effort is then verified through actual EMU tests on human subjects and the robotic space suit tester.

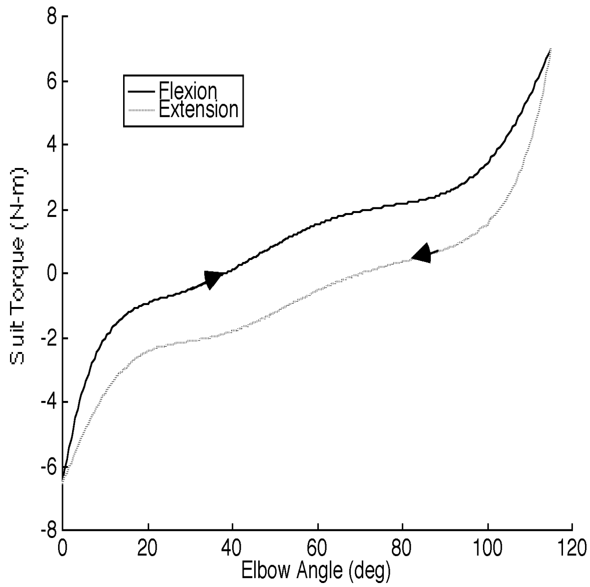

Figure 1. Hysteresis nonlinearity observed at the elbow joint of the EMU.

HYSTERESIS MODEL - Figure 1 plots the torque experienced by a suited astronaut flexing her elbow from a fully extended position to a fully flexed position (upper curve) and back again (lower curve). The plot exhibits a significant degree of hysteresis, revealing that suit-applied torques depend uniquely on the particular history and direction of arm motion. The soft EMU joints store the sequence of bunchings and expansions that work the TMG into a particular orientation and energy state; that unique state then dictates the amount of energy required to move the joint to another position.

Hysteresis is a key property of the suit joint, and must be carefully modeled. The approach is to develop a variant of the classical Preisach model for hysteresis, [15] which represents the hysteretic system *f(t)* as a weighted superposition of the simplest hysteresis operators, $\hat{\gamma}_{\alpha\beta}$:

$$f(t) = \iint_{\alpha \geq \beta} \mu(\alpha, \beta) \hat{\gamma}_{\alpha\beta} u(t) d\alpha d\beta \qquad \text{eq. 1}$$

where $\mu(\alpha,\beta)$ is a set of weights which define a particular hysteresis curve, α represents the switching value for a hysteresis operator during flexion, and β represents the switching value of a hysteresis operator during extension. This allows us to represent the joint workspace as a field of values, each representing the joint torque associated with changing direction of motion at a particular point in the workspace, as shown in Figure 2. Integration over the history of joint angles in the workspace then builds a magnitude for the total torque currently delivered by the suit. This method is implemented numerically as suggested by Mayergoyz [16] and delivered to the SD/FAST dynamics code as a user defined function which, given an input history of joint positions, applies an appropriate suit torque to each joint of the simulated EVA astronaut. These computations have been performed at the elbow, knee, and shoulder, and will eventually incorporate each of the EMU joints.

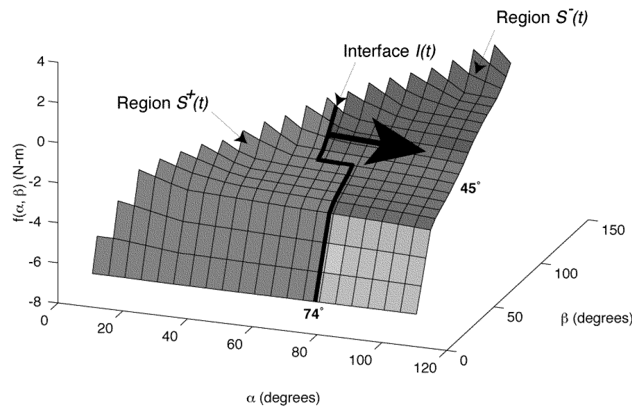

Figure 2. The surface $f(\alpha, \beta)$ at t=60 sec (elbow joint test). A value for f, the total torque applied by the EMU elbow joint, is calculated by integrating the shaded area based on equation 1. On this diagram, the first maximum was at 74° (α=74°), the first minimum was at 45° (β=45°), and the current input is u= α=64°, moving up the α axis.

SIMULATION METHOD - The suit model was demonstrated as a constraint on the existing 12-segment human model, which was created during the original simulations involving Intelsat recovery and Spartan payload manipulation. [11] The system allows us to describe a given EVA task in terms of hand trajectories, which are translated by the SD/FAST inverse kinematic solver into a history of joint rotations required to perform the task. Inverse dynamics routines then determine the torque required at each joint to produce the necessary joint rotations. The resulting time history of joint torques is used to compute the work done at each joint during the execution of a specific task.

Similar to earlier work, two simulations of an astronaut manipulating the 1,200 kg Spartan astronomy payload were performed; this time, however, each simulation was performed under two separate conditions: unsuited, to determine the baseline work level required to move the payload, and suited, incorporating the EMU suit model. The astronaut was required to move the Spartan payload along a circular trajectory while anchored to an inertially fixed foot restraint, as shown in Figure 3. The center of mass of each hand was welded to the payload and prescribed to move in a circular arc with respect to the inertial reference frame at a constant radius r = 0.15 m and total task time t = 10 seconds, providing a constant velocity of approximately 9.4 cm/sec. The crewmember's initial posture coincides roughly with human zero-gravity neutral posture. [9]

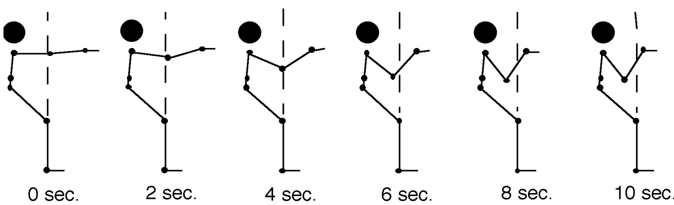

Figure 3. Sequential astronaut position during payload translation task, for the rigid lower body simulation.

For the first simulation, the astronaut's lower body and torso were locked in a rigid position, forcing the task to be executed by arm movement alone. Only the shoulder, elbow and wrist joints were allowed complete freedom of movement in three, one, and three degrees-of-freedom, respectively . The second simulation then introduced a compliant lower body, allowing full motion in all joints. Passive dynamic control was introduced at the ankle, knee, and hip joints to simulate postural control and relative muscle strength using the relation

$$\tau_{joint} = -k_{rot}(q_{joint} - q_{bias}) - b_{damping}\dot{q}_{joint} \quad \text{eq. 2}$$

allowing for joint stiffness k_{rot} and neutral position q_{bias}. Bias positions for the joints coincide with the initial zero-gravity posture, and realistic joint stiffnesses k_{rot} are used. [11]

RESULTS AND DISCUSSION

RIGID LOWER BODY - The cumulative shoulder joint work required to perform this task is shown in Figure 4. Relative to the unsuited condition, the suited astronaut does five times as much total work, even though there is no work done at the rigid hip, knee, and ankle joints. Work done at the shoulder is 27.5 times more for the suited case than the unsuited case. Almost all of the excess shoulder work is produced as a consequence of the simulation constraints. Unable to use his lower body, the astronaut moves his arms into inefficient areas of the suit workspace (near the joint limits) to complete the circular trajectory. At these extreme joint angles, he must exert a great deal of energy to maintain a smaller joint volume through certain portions of the task. Under normal circumstances, an EVA astronaut would never venture into these energy-intensive regions of the workspace. The following simulation reveals the ultimate effect this has on EVA performance.

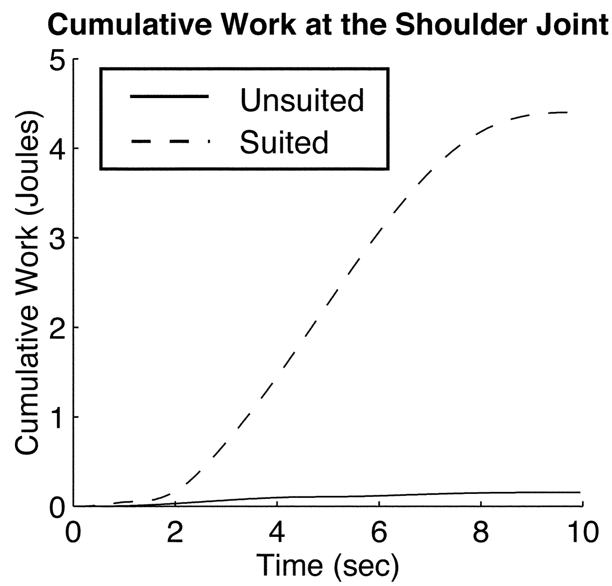

Figure 4. Cumulative shoulder joint work for payload translation task, for the rigid lower body simulation.

COMPLIANT LOWER BODY - Results of the compliant lower body simulation are shown in Figure 5, for both the suited and unsuited conditions. Allowing for a compliant lower body substantially reduces the work done at the shoulder joint. In fact, in the suited condition, the work done at the shoulder joint is less than 1% of the total work. Ankle work, however, increased by a factor of 3, as shown in Figure 6. With a compliant lower body, the total work required to accomplish the task was actually 27% less for the suited case than for the unsuited case.

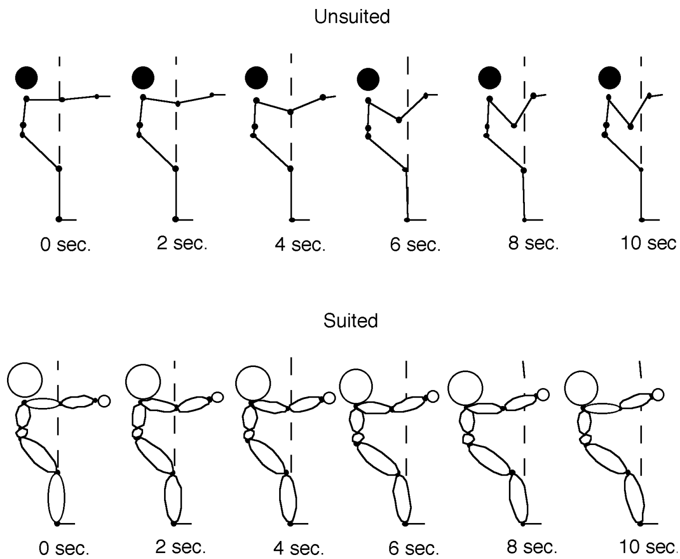

Figure 5. Astronaut position during payload translation task, for the compliant lower body simulation: shoulder work and ankle work displayed.

The striking difference between these results can be attributed entirely to the posture from which the astronaut performs the motion . Figure 7 describes crewmember shoulder position over time, comparing unsuited and suited conditions. The unsuited condition represents the posture to which the rigid astronaut was restricted; to achieve the required extension of the payload, his upper arm had to be pulled in close to his side. The suited, compliant astronaut manipulates the payload from a more suit-neutral posture, his arms floating easily in front of his body

Working with the suit close to a zero-energy neutral posture, more of the work performed actually translates to payload motion; previously, most of the work done was allocated to moving the shoulder joint. The total work required to complete the suited task with a compliant lower body is only 23% of that required in the rigid position, and 27% less than that required in the unsuited condition. Total work for the suited condition is less than for the unsuited condition because with a compliant lower body, the astronaut takes advantage of the long lever arm from shoulder to foot restraint, using his ankles to move the payload through the same distance while doing less work.

Although the compliant lower body solution appears optimal from an energy standpoint, it comes with serious drawbacks. The shoulder joint, though doing a premium of work to move the payload under the rigid-body condition, is supplied with relatively strong muscles. Consequently, the rigid lower body task, although inefficient, does not exceed the shoulder muscle capabilities. The small musculature about the ankle joint, however, is ordinarily used to supply the minor corrections necessary for balance during quiet standing. These muscles are not generally used to move massive payloads about in space; when called upon to do so, they may fatigue quickly under unfamiliar loads. These findings agree with anecdotal evidence provided by astronauts subsequent to certain EVA missions which have generated complaints of sore ankles, especially following the use of a foot restraint.

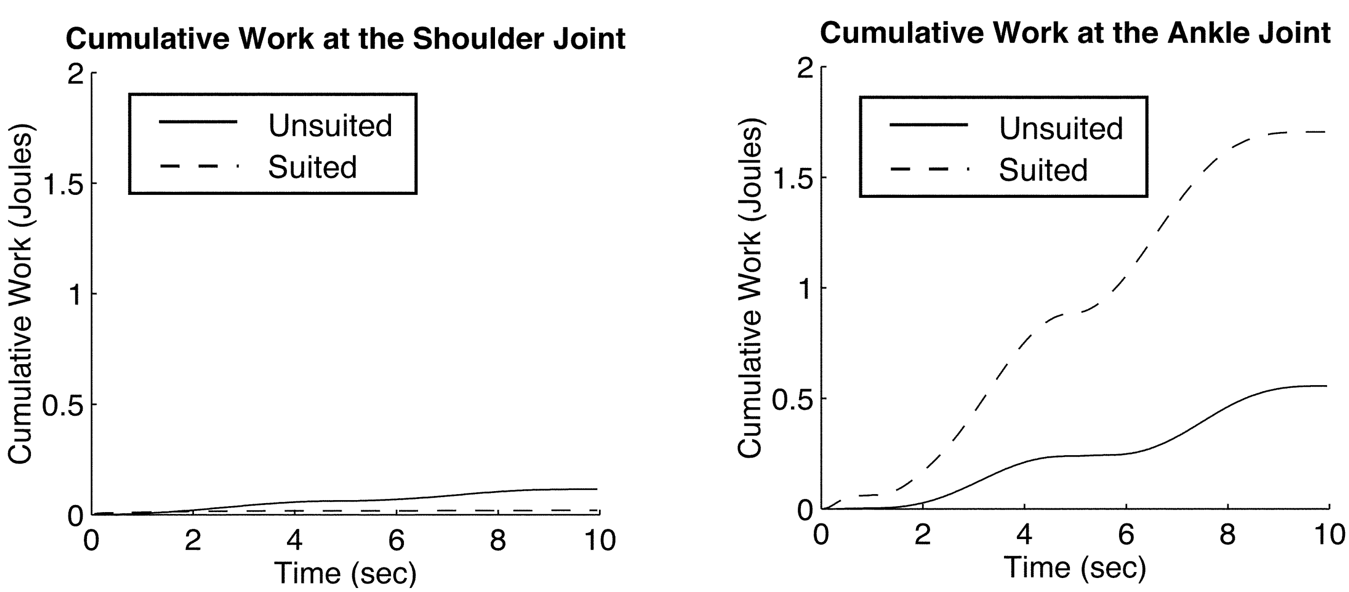

Figure 6. Cumulative joint work for payload translation versus time comparing unsuited and suited conditions.

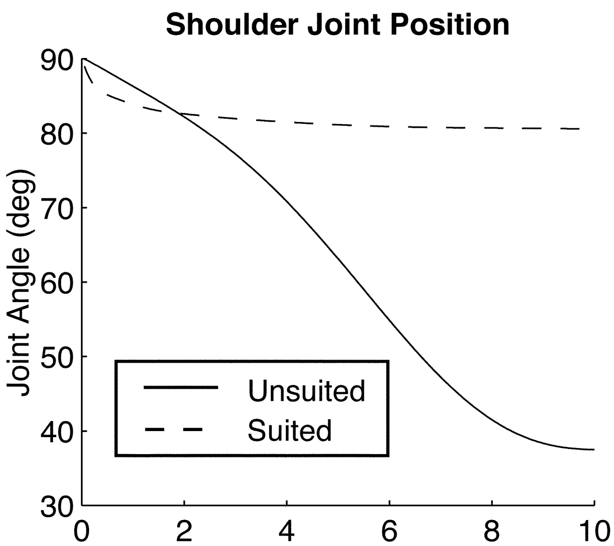

Figure 7. Simulated EVA crewmember shoulder position

Figure 8. Robotic Space Suit Tester wearing the EMU.

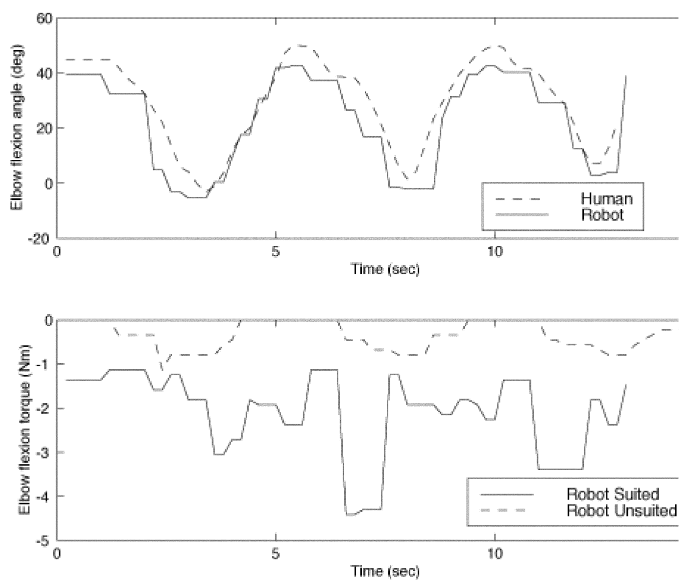

Figure 9. Representative experimental test data showing human test subject data and the commanded robot positions (top) and the resulting robot joint torques (bottom)

EXPERIMENTAL EMU TESTS - The experimental EMU tests resulted in a four-step process to obtain simultaneous joint angle and torque data. First, an unsuited human test subject performed a series of motions while arm and leg position data was recorded using an optical motion capture system. The human subjects then repeated the motions, wearing an EMU space suit, while three-dimensional kinematic data was recorded. The data were converted into joint angles for the Robotic Space Suit Tester (RSST) robot's joints, which then commanded the actual robot motion, both with and without a space suit, while the robot's joint angles and joint torques were recorded. Figure 8 shows the RSST wearing the EMU. Torques recorded by the robot in the unsuited condition are used to separate gravity-induced torques from the suited robot torque data, which results in suit-induced torques. The aforementioned hysteresis modeling, along with other methods, is used to relate space suit-induced torques to joint positions. A representative example of the experimental data collected for elbow joint angle for a human test subject and the robot are shown in Figure 9. The resulting joint torques recorded from the robot under both suited and unsuited conditions are shown in the lower plot. The joint torques recorded from the robot include a contribution due to gravity.

CONCLUSION

Although these simulated EVA missions would probably be successful regardless of the specific way in which they were performed, they point to important human factors issues which should be taken into account during EVA design. The postures suggested by the Spartan payload simulations indicate that ankle support may be a necessary part of future EVA foot restraints; alternative boot designs could be incorporated into the model for rapid-prototype analysis. The Spartan simulation also aids in task definition, restricting the available workspace by identifying regions of increased work and decreased task efficiency. These simulations can be used to develop a more comfortable working environment for the EVA astronaut, and help identify specific EVA tasks which might lead to unanticipated problems. The EMU suit model enhances the realism and validity of 6 dof dynamic simulations involving the execution of EVA tasks.

Future EVA models will incorporate greater physiological realism, and simulations will address issues related to the intelligent control of astronaut movement. Musculoskeletal models allow the transformation of joint torque values into muscle activation energies, which in turn will provide data relating to the work performed by specific muscle groups. Additionally, a forward dynamics simulation approach would remove the strict task definitions imposed by our task prescription/inverse dynamics method. Implementation of an astronaut movement control model will allow for forward dynamics solutions, driven by goal-oriented EVA tasks rather than rigidly defined limb motions.

ACKNOWLEDGMENTS

This work was supported by NASA grants NAGW-4336 and NAG9-1089.

REFERENCES

1. Reinhardt, A. "Results and Applications of a Space Suit Range-of-Motion Study." 19th Intersociety Conference on Environmental Systems, San Diego, CA.

2. Pardue, F., Pandya, A.K., Maida, J. (1996). "Creation of the Advanced Extravehicular Mobility Unit (EMU) Computer Graphics Model." , GRAF Facility, Lyndon B. Johnson Space Center, Houston, TX.

3. Price, L. R., Fruhwirth, M.A., Knutson, J.G. "Computer Aided Design and Graphics Techniques for EVA Analysis." 24th International Conference on Environmental Systems and 5th European Symposium on Space Environmental Control Systems, Friedrichshafen, Germany.

4. Dionne, S. (1991). "AX-5, Mk III, and Shuttle Space Suit Comparison Test Summary." 91-SAE/SD-004, NASA Ames Research Center, Moffett Field, CA.

5. Morgan, D. A., Wilmington, R.P., Pandya, A.K. (1996). "Comparison of Extravehicular Mobility Unit (EMU) Suited and Unsuited Isolated Joint Strength Measurements." Technical Paper 3613, Lyndon B. Johnson Space Center, Houston, TX.

6. West, P. R., Trausch, S., Stelly, C. (1989). "Space Suit Component Unmanned Torque and Range Measurement Test Plan." CTSD-SS-329, Lyndon B. Johnson Space Center.

7. Newman, D.J. and G. Schaffner, "Computational Dynamic Analysis of Extravehicular Activity: Large Mass Handling," AIAA Journal of Spacecraft and Rockets, 35(2): 225-227, 1998.

8. Hamilton Standard. "Mass Properties Report.", Hamilton Standard United Technologies, Windsor Locks, CT.

9. NASA. (1991). "Man Systems Integration Standards 3000."

10. Hollars, M. G., Rosenthal, D.E., Sherman, M.A. (1994). SD/FAST User's Manual, Symbolic Dynamics, Inc.

11. Schaffner, G., Newman, D.J. and S. Robinson, "Computational Simulation of Extravehicular Activity Dynamics During a Satellite Capture Attempt," AIAA Journal of Guidance, Control, and Dynamics, 23(2): March-April, 2000

12. Klaus, D. M., West, P.R. "Performance Evaluation of Advanced Space Suit Concepts for Space Station." 19th Intersociety Conference on Environmental Systems, San Diego, CA.

13. Menendez, V., Labourdett, X., Baez, J.M. "Performance of EVA Suit Mobility Joints: Influence of Driving Parameters." 23rd International Conference on Environmental Systems, Colorado Springs, CO.

14. Kozloski, L. D. (1994). U.S. Space Gear, Smithsonian Institution Press, Washington D.C.

15. Preisach, F. (1935). Z. Phys., 94, 277.

16. Mayergoyz, I. D. (1991). Mathematical Models of Hysteresis, Springer-Verlag, New York.