NASA TP-1998-3684

Understanding Skill in EVA Mass Handling

Volume III: Empirical Developments and Conclusions

Gary E. Riccio
Nascent Technologies

P. Vernon McDonald
Nascent Technologies

July 1998

Acknowledgments

The investigation described in this report would not have been possible without the expert assistance of several groups and individuals from NASA's Johnson Space Center (JSC). We thank the Anthropometry & Biomechanics Facility for providing hardware and technical support for data collection on the precision air-bearing floor (PABF). We also wish to thank Tom Smith, Frank Eades, Bill Lee, and John Harvey for their assistance in design and construction of the test hardware, and providing engineering and technical support in all phases of PABF operations. We thank Steve Anderson of ILC Dover for accommodating our investigation into the busy suit schedule, and providing the extravehicular mobility units (EMUs) and EMU technicians during our data collection runs. Special thanks go to our volunteer test subjects who provided their time, expertise, and invaluable comments on our test protocol. We would also like to acknowledge all of those individuals from the extravehicular activity (EVA) operational community with whom we have discussed this project over the course of its progress— including Richard Fullerton, Matt Mickle, Ken Bowie, Phil West, and Dom Del Rosso—for informing us about EVA practices, procedures, and lessons learned. Without their help, we could not have made our scientific investigation responsive to the needs of the EVA community. We are especially grateful to Jerry Ross, Leroy Chiao, and Jeff Hoffman for permitting an EVA-experienced crew member to participate in our study. We wish to thank Brian Peters, now at the University of Massachusetts, who went to great lengths to ensure the validity and reliability of our empirical data. Thanks also to the members of the Neuroscience Laboratory, NASA JSC, who supported this project from its conception. Finally, thanks to Dr. Dava Newman and two anonymous reviews for helpful comments on an earlier version of this paper. This project was supported by NASA grant 199-16-11-48.

Available from:

NASA Center for AeroSpace Information
7121 Standard
Hanover, MD 21076-1320
Price Code: A17

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Price Code: A10

Contents

Contents

(continued)

Figures

Acronyms

a-p	anterior-posterior
DOF	degrees of freedom
EMU	extravehicular mobility unit
EVA	extravehicular activity
ISS	International Space Station
ODS	ORU docking structure
ORU	orbital replacement unit
PABF	Precision Air-Bearing Floor
PFR	portable foot restraint
PLSS	portable life support system
R&D	research and development
YAC	yaw-axis cradle

Abstract

Key attributes of skilled mass handling were identified through an examination of lessons learned by the extravehicular activity operational community. These qualities were translated into measurable quantities. The operational validity of the ground-based investigation was improved by building a device that increased the degrees of freedom of extravehicular mobility unit motion on the Precision Air-Bearing Floor. The results revealed subtle patterns of interaction between motions of an orbital replacement unit mockup and mass handler that should be important for effective performance on orbit. The investigation also demonstrated that such patterns can be measured with a variety of common instruments and under imperfect conditions of observation.

1. Identification and Significance of the Research Issues

Spaceflight crew members encounter, and deal with, many circumstances unique to zero- or low-gravity conditions. Reactions an Earth-bound person might take for granted, or not even be aware of, fail to aid when adapting to spaceflight. Additionally, training measures created and administered on Earth might fail to adequately prepare a crew member for the unique environment. Given these challenges, successful extravehicular activity (EVA) operations are a testament to the *adaptability* and *skill* of crew members. Indeed the skill of the human operator has been the keystone to success of many, if not all, of the 38 EVAs performed to date. However, such levels of expertise are not easily attained. Only through the application of significant resources and highly detailed ground and on-orbit procedures have the EVA operations been possible. A conservative estimate indicates that there are at least 10 hours of mission-specific ground-based EVA training performed for each hour of on-orbit EVA performed, with many additional hours spent on contingency training. Moreover, the incremental nature of EVAs to date has permitted the training to be extremely task-specific and extremely detailed. EVA training, generally grounded in well-known scenarios, has been able to address a level of detail in time lines on the order of minutes. This level of detail is unlikely for future EVA training because of the accelerated progress required in EVA operations.

The scientific goal of the research described in this report is to identify and understand components of extravehicular (EV) mass handling skill by way of controlled testing in ground-based mass-handling simulators. This required the development of measures for components of mass-handling skill. The development of new measures was based heavily on our broader program of research on postural control and on simulators used for training. The theoretical underpinnings of our research and its application to EVA operations is summarized in Section 2. The new measures begin to provide an objective basis for assessing skill development and for developing training facilities in which the skills can be acquired. We consider the development of these measures to be the most important contribution of our investigation to ongoing research and development (R&D) to support EVA operations.

The operational goal of this effort is to *lower cost* and *increase efficiency* of skill-based training for EVA. For this reason, the empirical investigation of mass handling used NASA's principal mass handling simulator, the Precision Air Bearing Floor (PABF). The design of this investigation relied heavily on interactions with numerous individuals in the EVA community at Johnson Space Center (JSC) and NASA Headquarters. Only after extensive information gathering through conversations with such individuals and through review of existing documentation on EVA operational procedures were we able to design a simulation with sufficient fidelity for mass handling on the PABF. Information and conclusions from this phase of the investigation addressed:

a) The relation between the experiments and operational considerations in EVA
b) The key scientific principles behind the relation between crew member (postural) restraints and mass handling
c) Methods that should be used to study the relation between postural restraints and mass handling
d) The design and use of ground-based simulators for the development of EVA skills such as mass handling.

Our conclusions from the interviews, review of EVA documentation, methodological development, and data-collection on the PABF are that skilled mass handling requires the following:

1) Sensitivity to the relationship between postural stability and manual control
2) Sensitivity to the relationship between postural stability and postural configuration
3) Sensitivity to the relationship between postural equilibrium and postural configuration
4) Management of the tradeoff between postural stability and mobility
5) Sensitivity to the effects of postural configuration on visibility and reach
6) Control of force couples at the orbital replacement unit (ORU) and restraints with respect to the consequences for multiaxis postural perturbations
7) Sensitivity to the inertia tensor of the manipulandum with respect to its trajectory, its location and orientation, and the manual forces involved in moving it

These issues provide a framework for design and evaluation of simulators in which EVA skills are acquired or used. They led to a modification in the PABF for the empirical component of our investigation. The modification is discussed briefly in Section 3.6. We consider this to be the second major contribution of our investigation to ongoing EVA R&D.

This report focuses on the data-analytic techniques that we developed to address issues a-c. We believe that these techniques have much broader application than in the empirical investigation conducted in the PABF (summarized in Sections 3-5). Results from our PABF investigation are instructive for the general application of our techniques to problems ranging from design and evaluation of EVA simulators to design and evaluation of advanced space suits. Data from one subject are presented graphically to illustrate the use of our techniques and interpretation of the results that they provide (see Section 5). We consider the pedagogical value of these results to be the third major contribution of our investigation.

2. Theoretical and Empirical Foundations

2.1 Related Research by the Investigators

Our research on postural control and human-environment interactions [1-7] and exploratory behavior in skill acquisition [8-10] provides an appropriate scientific foundation for the study of human adaptability and skill in EV mass handling. This research has led to the development of measures, for manual interactions between individuals and the substantial environment, that plausibly are observable by human sensory systems (i.e., anthropomorphically valid measures). These measures also are especially sensitive to the peculiarities of weightlessness. This provides for the possibility of synergistic research conducted on Earth and on orbit. Fundamental considerations in our systematic program of research are summarized in Riccio et al. [11] and in McDonald et al. [12]. These considerations are highlighted below.

Some of the most important EVA investigations and Detailed Test Objectives to date have analyzed the crew member as a mechanical element of an EVA system. Our investigation addresses the fuzzier concept of skill, specifically the skill of crew members in performing various tasks in weightlessness. Skilled movement and interaction with the environment depends on the mind as well as the body of the crew member. We consider this fundamental mind-body coupling within a multidisciplinary context that attempts to span biological and behavioral science (e.g., psychology, kinesiology and neurophysiology) as well as bioengineering. More specifically, we examine this coupling from a unique perspective on adaptive control by human beings [13]. From a control-theoretic perspective, the mind is analogous to the "controller" which instantiates mappings between observable and controllable states. The body is analogous to the "plant" through which states are controlled. The mechanical and control-theoretic approaches to human-environment interactions complement each other. The former focuses on quantification of dynamically stationary properties while the latter focuses on organization of adaptive elements into systems that satisfy particular objectives over uncertain or changing conditions.

We describe our perspective as control theoretic because it draws more on fundamental concepts about control systems in engineering than it does on working constructs from the subdisciplines of biomechanics and motor control in the bio-behavioral sciences. We have attempted to identify the theoretical underpinnings of control-systems engineering that are most relevant to control by human beings [13]. We believe that these underpinnings are implicit in the assumptions that cut across diverse methods in control-systems engineering, especially the various methods associated with "nonlinear control," "fuzzy control," and "adaptive control." It is our intent to build on such theoretical foundations rather than on the mathematical formalisms that are associated with particular methods in control-systems engineering.

Many formalisms within control-systems engineering are ready to be exploited in the analysis of human environment interactions. This interdisciplinary work can be productive only if the meaningfulness and representativeness of the associated mathematical entities and operations are established with respect to human biology and behavior. In other words, we need to build on a well-understood mapping between the formal system (the mathematics) and the empirical system (human biology and behavior). Understanding this measurement-theoretic mapping can only be as good as the understanding of the formal and empirical systems. While the formal systems of control-systems engineering are sufficiently mature for application to adaptive systems, the understanding of human biology and behavior is not adequate in the context of realistic interactions with the surroundings. The remainder of this section attempts to identify aspects of human biology and behavior that are sufficiently complex and, at the same time, sufficiently simple to support interdisciplinary control-theoretic investigations of EV mass handling.

2.2 Selective Loss of Detail in the Analysis of Complex Systems

Human-environment interactions involve the control of complex systems. Obvious sources of this complexity are the multiple body segments that each move in multiple degrees of freedom (DOF) under the influence of multiple inputs (i.e., forces and sensory information). Our analysis of such systems is simplified by considering low-dimensional models or approximations that reflect the constraints on the system and within the system [5]. We give special emphasis to constraints that are imposed by the goal of the human-environment interaction; that is, we focus on task constraints that define and bound the relevant subsystems. A precision manual-control task, for example, requires that we consider stability of the shoulder relative to the manipulandum along with factors, including postural configuration, that influence such stability [1]. Our style of reduction is inspired by analysis and synthesis for aircraft control systems (e.g., [14]). In such work, exceedingly complex aerodynamics are strategically simplified by focusing on the exigencies for control (i.e., the maintenance of stable flight). Removal of unnecessary analytical detail is even more aggressive in the design of flight simulators, for example, by considering the capabilities and limitations of observation and control by a human operator (e.g., [2, 15]). Thus, while our approach to postural control may be novel, it is grounded in well-established methods for analysis of complex dynamical systems.

Our treatment is based on the assumption that individuals, in the context of their surroundings, are adaptive nonlinear control systems with multiple levels of nesting, multiple inputs and multiple outputs. Analysis of all control systems begins with identification of the functions of the system. These functions or tasks determine which states of the human-environment interaction are relevant and which states are irrelevant regardless of how common or familiar they may be in other treatments. Stability of the system is possible if it is controllable and observable. The system is controllable if the task-relevant states are modifiable by the actions of actuators or effectors in the system (i.e., there is a mapping between dynamical states and outputs of subsystems). The system is observable if these states are represented in the stimulation of the sensory systems (i.e., there is a mapping between dynamical states and the inputs to subsystems). *Observability* and *controllability* are sufficient conditions for stability of control systems, in general, but they are not necessary conditions for stability of systems that are quite common in nature (described below).

The most important aspects of the human-environment interaction in our investigation of EV mass handling are the functional consequences that body configuration and stability have for the pickup of information or the achievement of overt goals. It follows that an essential characteristic of postural behavior is the effective maintenance of the orientation and stability of the sensory and motor "platforms" (e.g., head or shoulders) over variations in the human, the environment, and the task [1]. This general skill suggests that individuals should be sensitive to the functional consequences of body configuration and stability. In other words, individuals should *perceive the relation* between configuration, stability, and performance of perception and action systems so that they can adaptively control their interaction with the surroundings [7]. In our investigation, we have identified a level of analytical detail that is sufficient to appreciate such relations and their role in adaptive control. This often requires that we prudently set aside unnecessary quantitative assumptions suggested by related disciplines so that we do not miss the qualitative properties that define or bound success and failure in human-environment interactions [1, 13].

Human-environment interactions can be analyzed in terms of component subsystems. It is useful if the subsystems can be understood in isolation and in the ensemble using the same conceptual framework and methods. Postural control and manual control subsystems of the human body meet these criteria as do objects and devices in the physical environment. These interacting subsystems in a human-environment interaction often are inherently stable in some, but not necessarily all, DOF or over certain parametric ranges. Only the remaining states of the system as a whole (those that are inherently unstable or neutrally stable) need to be managed explicitly by the control system (the rest takes care of itself). The system is described as detectable when there is a mapping between these dynamical states and the inputs to the sensors. The system is described as stabilizable when there is a mapping between these states and the outputs of the effectors. Stabilizability and *detectability* are necessary and sufficient conditions for the control of such partially stable systems.

The strategy outlined above can be used to evaluate facilities and systems that are designed to simulate non-terrestrial conditions and to familiarize individuals with those conditions. It offers an anthropomorphic basis for prioritizing the many factors that must be considered in replicating or neglecting attributes of a complex environment. We consider the essential attributes for a high-fidelity simulation to be those that relate to the stabilizability and detectability of particular human-environment interactions. Further simplification is possible because some attributes that are required for one task may be unnecessary or incidental to performance on a different task. That is, simulator fidelity is task *specific* and evaluation of fidelity should be *selective*. Fidelity may be adequate if there is qualitative correspondence between the simulator and the simulated environment (i.e., categories of information and control parameters are represented). Quantitative precision in simulation of complex systems may be relatively unimportant [2, 16]. Finally, the design of the simulation should take into consideration whether it will be used for training particular skills or to provide an operationally valid milieu for developing plans and procedures. These factors guided the modification of the PABF in our investigation.

2.3 Common Constraints on Postural Control

Limb- and body-pendulum dynamics in general, and balance in particular, are pervasive properties of human-environment interactions in the terrestrial environment. This is important to consider because such dynamics are part of the context in which general postural skills are developed [7, 17]. Constraints that are specific to pendulum dynamics are imposed by gravitational and resistive inertial forces. The sum of these forces is sometimes referred to as the gravitoinertial force vector (see e.g., [18] pp. 1046-1051). The magnitude of the gravitoinertial vector is nonzero whenever a body is in contact with a support surface, and the direction of this vector generally determines the direction of balance or equilibrium for a body in contact with a surface of support [7, 19]. When the orientation of the body deviates from the direction of balance, torque is produced by the non-alignment of gravitoinertial and support surface forces. Alignment with the direction of balance minimizes the torque or effort required to maintain a particular orientation.

It is not always appropriate to align with the direction of balance. The goals of perception and action often require other orientations or configurations [5]. Nevertheless, orientation with respect to the direction of balance has *consequences* for control in most terrestrial conditions. Such consequences are due, in part, to fluctuations in orientation which become more variable and asymmetric as tilt from the direction of balance increases [1, 4]. Sensitivity to these consequences presumably is an important component of postural skill. The nature of these consequences is quite different under conditions of weightlessness in which the gravitoinertial magnitude is zero and in which balance dynamics are absent [7]. We believe that changes in postural orientation and configuration in a high-fidelity mass-handling simulator should correspond, at least qualitatively, to those on orbit. Qualitative correspondence means that DOF that must be stabilized by the crew member on orbit also should be inherently unstable in the simulator while the quantitative characteristics of the instability are relatively unimportant.

The controllability of orientation is also constrained by the properties of the support surface [5-7]. Pushing on support surfaces with the legs and arms can be used to compensate for torques due to tilt or imbalance (cf., [5, 20]). The efficacy of such action depends on the resistance (e.g., mechanical impedance) provided by the support surface, thus, skilled use of a support surface for postural control requires knowledge (tacit or explicit) of the resistance it affords. Pushing on surfaces of moveable objects (potential support surfaces) can complicate postural control when it leads to inappropriate motion of task-relevant objects in a work space. Postural control must take into account such relative motion between the body and task-relevant objects so that deleterious consequences for task performance are minimized. A skilled EV crew member, for example, presumably knows (tacitly or explicitly) the difference between a foot restraint with some "slop" and one that is completely rigid with respect to the effects on mass handling performance. The crew member could make corresponding adjustments in postural control during mass handling.

Such adjustments may be as simple as changes in the stiffness of the body, but they are no less skilled.

Constraints on postural control are not limited to objects with which the body is in physical contact. Both the visual system and the manual-control system are "nested" within the postural control system [21-23]. This means that these subsystems have some separate and some shared effectors or feedback loops (and associated neural pathways); that is, they are mechanically or informationally connected [2, 13]. Postural orientation and configuration may be modified to facilitate perception of objects in the environment. For example, an EV crew member may adjust the configuration and orientation of the body in order to see around an ORU to a potential site of docking. Nonmechanical constraints may be especially important in the absence of balance dynamics as in weightlessness. In weightlessness, mechanical and nonmechanical interactions with objects and support surfaces are the major determinants of postural *equilibrium* and *stability*. Higher-level (meta) knowledge about the fact that such interactions have consequences for task performance facilitates learning or adaptation to novel conditions in which the consequences are different in nature. Accordingly, we believe that exposure to the existence of such consequences in a simulator (i.e., qualitative correspondence) is sufficient for *learning to learn about the details (i.e., quantitative characteristics) of the consequences on orbit.*

2.4 Information in Movement Variability

Human-environment interactions constitute robust systems in that individuals can maintain the stability of such interactions over uncertainty about and variations in the dynamics of the interaction. Robust interactions allow individuals to adopt orientations and configurations that are not optimal with respect to purely energetic criteria. Individuals can tolerate variation in postural states, or in movement trajectories, with respect to simple optimization criteria. People may sway with respect to the direction of balance, for example, or they may not move smoothly from an initial state to a goal state. In addition, people rarely perform a movement task in exactly the same way from trial to trial. In human movement science such variation is conventionally referred to as "movement variability." The premise of the methodology developed in our investigation is that movement variability can serve an important function in adaptive systems.

Postural variability generates stimulation which is "textured" by the dynamics of the human environment system [1, 6, 13]. The texture or structure in stimulation provides information about variation in dynamics, and such information can be sufficient to guide adaptation in control strategies. In control-systems terminology, variability provides for the *persistent excitation* that is important for adaptive control [24-25]. Excitation (i.e., stimulation) is persistent, and thus affords adaptation, to the extent that it spans the task relevant state space for the system (i.e., human-environment interaction). If stimulation spans the entire range of states over which dynamical variability occurs, then it is *sufficiently rich* to specify this variation and, consequently, to support adaptive control. The data analyses summarized in Section 4 were developed to measure informative patterns of movement variability. We believe that such measures ultimately will allow us to evaluate human movement with respect to criteria that are analogous to persistent excitation and sufficient richness.

Adaptive control does not require explicit identification of system dynamics. In the mathematics of adaptive control, systems in which adaptation is driven by explicit identification and comparison to a model are formally identical to those in which adaptation involves attunement to statistical regularities without explicit identification or comparison to a model [24-25]. Any differences between the two types of adaptive control would derive from the way in which one accesses or interacts with the knowledge that the adapted system embodies. There are deep issues in psychology and philosophy surrounding the analogous distinctions in human perception and performance. Thus we cannot say that systems identification is important or inconsequential to human learning and behavior. In the behavioral sciences, the presence or absence of systems identification is relevant to pedagogy and transfer to training. In engineering, it is relevant to troubleshooting and redesign of a control system. In any case, persistent excitation and sufficient richness are important for adaptive control whether or not there is explicit identification of system states because they determine the validity of interpolation and extrapolation from prior experience. Our interpretation of results from several investigations assumes that human beings perceive dynamics in movement variability. It should be noted, however, that this assumption is unnecessary for our contention that movement variability plays an important role in skilled human behavior.

Riccio [1] presented evidence that movement variability can inform individuals about the dynamics of their own movement systems or about the dynamics of their interaction with the environment. This suggests caution in the use of perceptual or biomechanical models that treat movement variability as noise in the system. Noise, by definition, is neither informative nor controllable. If movement variability is informative, it would be adaptive to modify the characteristics of variability in order to facilitate the pickup of information. Modification or control of movement variability may be as simple as increasing (or not minimizing) the magnitude of variation so that patterns are more salient. Such considerations emphasize that informativeness and controllability of movement variability should be included in models of human-movement systems. Measurement of informative patterns in movement variability is an important part of the methodology developed in our investigation of EV mass handling (summarized in Section 4).

Riccio [1] described a study that provided a compelling demonstration of the informativeness and controllability of movement variability. The study looked at performance and learning in a two-person balancing task in which one person ("top") stands on the hands of another person ("base"). The advantage of this task is that standing balance is a familiar activity and, as such, provides a foundation for the two-person coordination in this task which has to be learned. (An interesting feature of the task is that it is similar to a procedure developed for an STS-61 EVA in which one crew member "stood" on the hands of another crew member in order to facilitate access to a section of the Hubble Space Telescope that required insertion of an ORU.) It is well known that particular body configurations (e.g., relations between upper torso and legs) are essential to skilled performance in this task, as other configurations are to a lesser extent for stance in general [5]. The preferred configurations changed systematically in both beginners and experts when the base modified the dynamics of the task by pulling excessively on the heels or the toes. It was hypothesized that adaptation to this dynamical variability was based on systematic patterns in the variability of foot movement.

The feet were an important focus for informative variability in this task because they provided the medium of communication between the top and the base. Body configuration and foot angle were measured through frame-by-frame analysis of videotape. Stability was operationally defined in terms of the *standard deviation* of foot angle within each second of data. Equilibrium was operationally defined in terms of the *skewness* of foot angle within each second of data. Nonequilibrium movements (i.e., tending to fall backward or forward) would be characterized by foot movements that were larger or more frequent (i.e., skewed) in plantarflexion or dorsiflexion. Finding and maintaining equilibrium involved controlled adjustments in body configuration, from second to second, that symmetrized the movements of the foot. "Response surface" manifolds described the relation between configuration and either stability or equilibrium. The manifolds were derived using Distance-Weighted Least-Squares Regression. The relation between configuration and standard deviation generally was saddle-shaped, and trajectories were attracted to the seat of the saddle. This means that subjects did not (in)tend to minimize variability of the foot movement. Minimum variability can occur in states, such as leaning, in which the body is especially stiff. Such states are not very robust to perturbations, and they cannot be maintained for very long.

The subjects tended to reduce variability to, but not below, a level that was associated with symmetrical movements. This suggests that a certain amount of variability may be necessary to notice an asymmetry in movement. Both beginners and experts symmetrized movement, but the beginners may have required more variability in order to perceive symmetry. This interpretation is consistent with a psychophysical approach to *fuzzy observation* and control in realistically noisy conditions [1, 4]. The need for such an approach is one way in which explanation of human systems differs from physical systems. The pickup of information (observation of system states) by human beings is not an all or none process. Detection of sensory patterns or events is probabilistic in that it is influenced by hidden factors such as fluctuations in attention. The probability of detection generally is influenced by the measurable characteristics of the event such as amplitude or contrast in relation to commensurate characteristics of noise or unrelated events. We sought an extension of the response surface methodology in our EVA investigation that would allow us to speculate about "signal" and "noise" in the patterns of movement variability (see Section 5).

2.5 Multicriterion Control of Posture

Performance on many tasks is influenced by body configuration and movement, but a task is not necessarily defined in terms of body configuration and movement. Postural configuration influences how close the eyes are to potential objects of regard and whether the objects are in the field of view. Postural configuration also influences whether potential manipulanda are within the functional reach envelope. Postural adjustments may be required (a) for looking at, around, and through; (b) for touching, reaching around or reaching through; or (c) for regulating postural movements. Postural movement (e.g., instability) influences the precision of vision and prehension. Together, configuration and stability have consequences for the ease or difficulty of seeing and manipulating objects [6]. Thus, visual or manual control performance provides evaluation functions for postural configuration.

Riccio [1] described a study that assessed the functional topological relations between postural configuration and performance on a manual control task. The manual task required that the subject tap at a constant rate. The nested-systems analyses focused on the relations between postural configuration and either *variability* of tapping force or variability of intervals between taps. Response-surface manifolds were derived using distance-weighted least-squares regression. Variability of force was increased by bending and decreased by leaning. The effect of leaning apparently was due to a decrease in relatively high-amplitude low-frequency sway that results from stiffening of the body in order to prevent falling. The increase in force variability with bending may reflect an instability that can be tolerated because there was not a threat of falling in these configurations.

The manifold for timing indicates a shallow gradient along the locus of postural configurations in which torques due to upper- and lower-body tilts tend to counterbalance each other [5]. This is consistent with the expectation that interval variability reflects effortfulness. Variability of tapping intervals has been used by the human-factors community as a reliable measure of work-load in various perceptual-motor tasks [1]. The manifold also shows a distinct asymmetry in interval variability with respect to anterior and posterior leaning. This probably reflects the relative difficulty of posterior leaning due to extension of the arms in order to reach the keyboard.

The correlation between variability of force and variability of intervals was essentially zero. This indicates that force and timing are influenced by different factors in such tasks. The low correlation between force variability and interval variability is consistent with the hypothesis that the former is influenced by postural stability, the latter is influenced by postural effort, and that stability and effort can vary independently. Such results emphasize the importance of considering *multicriterion control* in any evaluation of coordination between postural control and manual control [13].

More generally, multicriterion control results from the addition of task or informational constraints to purely mechanical constraints on postural control. Task constraints are a general property of human environment interactions [5]. Task constraints can have similar effects to mechanical constraints even when there is no contact between the human body and the surroundings, although the causal connection is quite different [1, 3, 5]. An important issue in any approach to multicriterion control is the commensurability of such diverse constraints on a system and their combination in an evaluation function for control of the system. We have attempted to develop a methodology within which multiple task constraints and mechanical constraints on postural control are commensurable [1, 5]. The response surface analyses summarized in Section 5 are our methodological foundation for investigating multicriterion control of posture in this and other investigations.

3. Experimental Methods

3.1 Subjects

Subjects were all volunteers who had passed the Air Force Class III physical and had undergone the NASA Physiological Training program. Subjects were primarily selected to cover a broad range of EVA-related, suited, mass-handling experience. Of the five subjects selected, two were complete novices to the extent that their only experience of EV mass handling occurred within the context of this investigation, and was thus limited to activities on the PABF. Two other subjects had previously performed suited mass handling on the PABF, in the Weightlessness Environment Training Facility, and on the KC-135 during parabolic flight. Consequently these two subjects could be considered relatively experienced in extravehicular mobility unit (EMU) activities in all the available simulators. The fifth subject had the most extensive range of experience, having performed on-orbit EVAs. This subject had performed four Shuttle mission EVAs for a total of 25 hours of on-orbit EVA. Analysis of data from all subjects is ongoing. Data from one of the experienced subjects (not the astronaut) are presented in this report. The intent of this preliminary report is to illustrate the methodology and the basic elements of postural control that it addresses.

3.2 Task

A requirement of our task was that it should capture some fundamental elements of EV mass handling skill. For reasons summarized in Sections 1 and 2, we concluded that the task should require various degrees of coordination between postural control and manual control. Thus, the task should require the following attributes:

a) Fine positioning of a large mass in multiple DOF

b) Transition in postural configuration during mass handling

c) Variation in location of the foot restraint relative to the work space

d) Variation in constraints on mobility due to the EMU and associated crew member restraints

It was not necessary for the physical setup to look exactly like any particular on-orbit EVA as long as it allowed the task to include generic components of EV mass handling. Of course, the task also had to be implemented on the PABF and thus was constrained by the nature of the simulator. Eventually we devised a task that entailed the translation of a mass from one body-relative location to another in order that the mass be docked into a docking receptacle. The presence of both translation and docking components in this task increased its relevance to many on-orbit mass handling activities. Data from translation and docking components of each trial were combined in the analyses presented in this report.

The precision required for the docking task was also manipulated in this investigation. In the high-accuracy conditions, there was a 1.25-cm gap between the ORU and the opening in the docking structure in the fully docked position. In the low-accuracy condition, there was a 5-cm gap around the ORU in the fully docked position. Only data from the high-accuracy condition are presented in this report. Within each accuracy condition, we manipulated the constraints on the ORU trajectory. In some trials, the trajectory for translation and docking was in the midsagittal plane of the subject's body because of the height of the recumbent subject above the floor. In other trials, the subject's midsagittal plane was above the centroid of the ORU handle. Subjects generally rotated their body in the yaw axis in this condition. The resulting trajectory of the ORU was oblique to the subject's midsagittal plane. Only data from the oblique trajectories are presented in this report.

The components of our experimental apparatus included an EMU, a 5-DOF ORU, the ORU docking structure, a novel assembly for the EMU and its supporting air-bearing sled, and a PFR and its attachment structure. These components of the apparatus are briefly described in the following sections (see also [12]).

3.3 EMU

A Class III EMU was used for PABF testing. This EMU is virtually identical to the CLASS I system used on-orbit except for the portable life support system (PLSS) mockup because air and cooling are provided by remote means. Prior to EMU operations, anthropometric measurements were made so that an appropriately sized EMU could be constructed. The EMU is comprised of multiple components, each of which can vary in size, according to the proportions of the wearer. After the EMU was assembled, each subject proceeded through a "fit check" to validate the fit and comfort of the EMU.

3.4 ORU

The ORU for this test was based on a generic International Space Station (ISS) component—the Rocketdyne "battery box." This component was to be used in the STS-80 EVAs. The mockup of this ORU was constructed using unistrut, and it approximated the flight component volumetrically. The mass and inertial properties were different than the flight component. The degree of dissimilarity depended upon the axis of motion. The unistrut frame was supported at the geometric center by an air-bearing ball which permitted limited rotation in pitch, yaw and roll. The air-bearing ball was in turn supported by an air-bearing sled so that the ORU-sled mass could be translated within the plane of the PABF. The unistrut frame was neutrally balanced by the addition of lead plates within the frame. The entire mass of the ORU was approximately 250 kg.

A prototype D-handle microconical ORU handling tool was fitted in the (subject-relative) left-superior quadrant of the ORU. Consequently, the midpoint of the handle (i.e., microconical fitting) was not located on a principle plane of inertia, such that cross-coupled moments would be encountered upon attempts to move the ORU. The handle was fitted to a 6-DOF force-torque transducer, which in turn was rigidly attached to the ORU structure. The transducer allowed the measurement of the forces and torques applied to the handle and thus to the ORU during the docking task.

3.5 ORU Docking Structure

A rigid and immobile ORU docking structure (ODS) for the battery-box mockup was constructed from unistrut and assembled such that yielding to the forces encountered during contact with the ORU was minimized. A rigid backstop at a depth that is equal to the depth of the ORU was included in the ODS. Corners and catch points on the ODS and ORU were eliminated so that docking was as smooth and as operationally valid as possible.

3.6 Enhancement of the Mass Handling Simulator

A pivotal development during the investigation was a modification to the PABF. The PABF, located at JSC, comprises a high-precision stainless steel surface 7.31 m wide x 9.75 m long made up of 32 steel plates (.915m x 2.44m x .1525m each) leveled to ±0.254 mm over the extent of the floor. Masses are supported on sleds equipped with pads, usually placed in a triangular array, through which compressed air is forced. The air forced through the pads raises the sled approximately .075 mm, and the mass thereon, above the floor so that it rides on a cushion of air. Consequently, the mass is moveable with minimal friction in 3 DOF. An additional air bearing, which can be placed onto a sled, is able to add two further "frictionless" DOF, giving a total of 5 DOF. The air bearing is usually used to support masses being handled so that one may experience the orbital dynamics of mass handling.

Typically, the PABF has been used for mass-handling activities while the "handler" stood upright, or with the handler lying on one side (recumbent) on an air-bearing sled. The upright configuration allows for multiaxis postural perturbations, but the restraints required for suspension can qualitatively change the dynamics of movement in various postural DOF. The recumbent configuration minimizes configuration dependent stimulation of the otolith organs, as on orbit, but it does not allow for postural movement in the body-yaw axis. We concluded from our interviews and review of EVA documentation that an important part of mass-handling skill involves stabilization of the body in orthogonal planes (i.e., management of multiaxis perturbations). It was thus crucial that we provide sufficient postural movement in yaw as well as in pitch. The yaw-axis cradle (YAC) was designed for use with the EMU in the recumbent orientation on the PABF.

Figure 1 shows a photograph of the YAC frame, and Figure 2 shows the YAC fully integrated into the experimental setup. While in the recumbent orientation in the YAC, the subject was restrained using a portable foot restraint (PFR) similar to those used on orbit. The YAC frame was designed such that the axis of rotation would pass through the center of mass of the human-EMU-frame system and with this axis perpendicular to the plane of the EMU waist bearing.

As a safety measure, the bearings were limited to ±15 degree rotation by the use of physical stops. This limit rarely impaired yaw rotation during any subsequent testing. The frame of the

YAC attached to the PLSS-EMU, and thus essentially became an extension of the hard upper torso unit of the EMU. The frame was then set into place in a cradle such that the yaw axis was 109 cm above the PABF. The placement of the YAC-EMU assembly on the air-bearing sled was designed so that the subject in the EMU protruded slightly over the leading edge of the sled. This minimized the interference of the YAC sled with the ORU sled during the docking task. The EMU, and thus the subject, was always placed into the YAC in a left-hand-down orientation. Once in the YAC, the subject's feet were locked into the PFR. The lower torso unit was then counterbalanced with attached weights to minimize yaw torque. The YAC permitted four potential DOF of postural movement. In some conditions, we eliminated DOF by either locking out the potential for yaw rotation and/or turning off the air for the sled. Consequently, without yaw rotation there were only three potential DOF of postural movement. Postural movement could be reduced further to essentially zero DOF by eliminating the action of the air-bearing sled. The results summarized in this report are from the condition in which the YAC had four DOF of mobility.

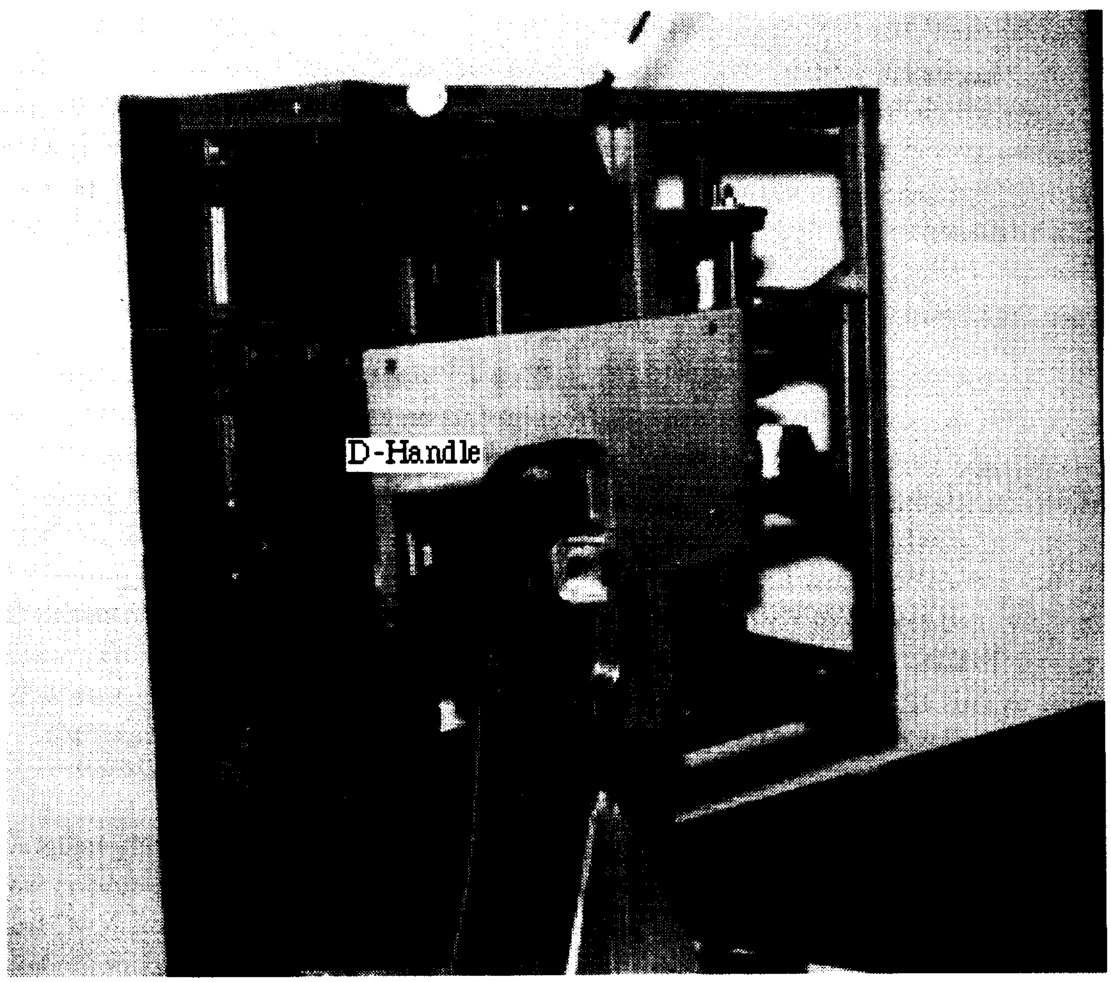

Figure 1: The orbital replacement unit with the D-handle sitting at the opening of the docking structure. The handle was instrumented with a 6-DOF force-torque transducer.

Subjects with little or no prior experience in the EMU and in simulated EV mass handling did not typically notice the yaw motion that they produced during mass handling. However, one subject with prior experience in these conditions did notice yaw mobility and commented favorably about this attribute of the YAC. Overall, the YAC appears to be a valuable addition to the complement of devices that are used in the PABF facility.

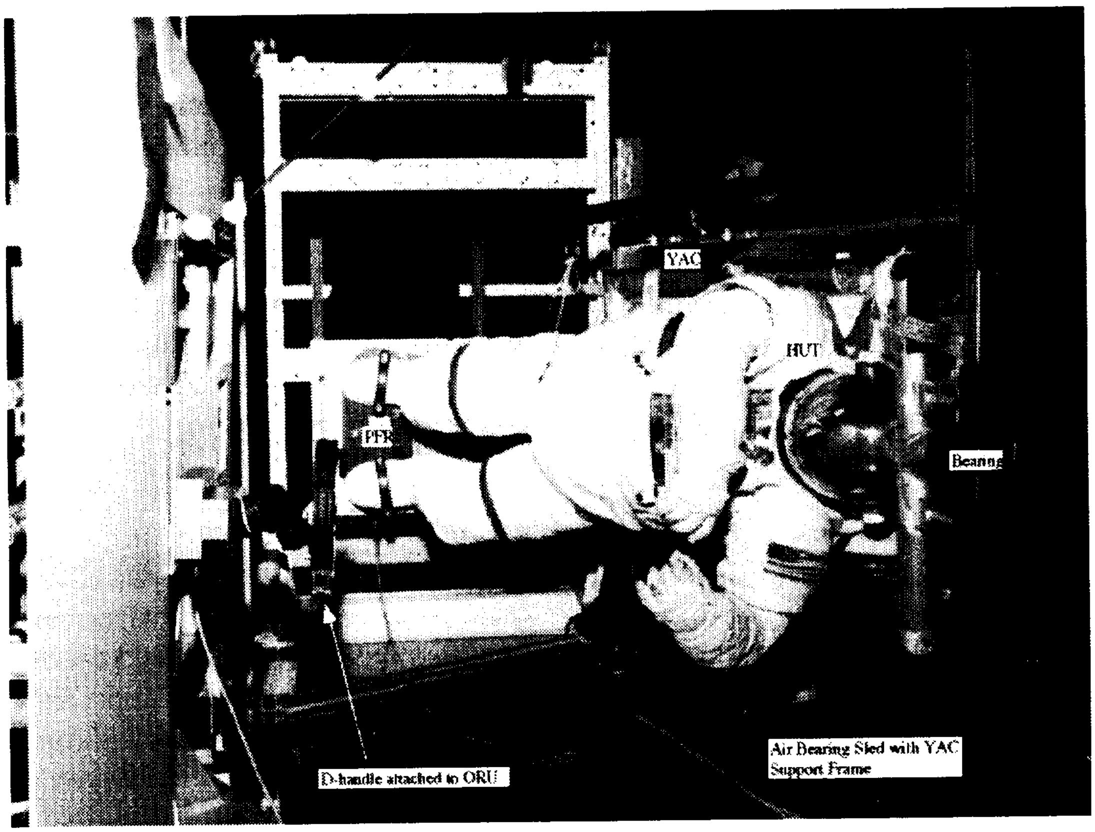

Figure 2: The experimental layout with a subject in the extravehicular mobility unit supported in the yaw axis cradle. Orbital replacement unit is docked.

3.7 Portable Foot Restraint and Attachment Structure

While in the recumbent orientation in the YAC, the subject was restrained using a PFR similar to those used on orbit. The feet were restrained during all phases of this investigation. The PFR was attached to a superstructure with a mass in excess of 1000 kg. This superstructure also possessed sufficient rigidity so that there was no noticeable yielding to forces and torques applied through the PFR. The PFR was instrumented with a 6-DOF force-torque transducer. This transducer was used to measure the forces and torques applied to the PFR during the docking task. The PFR attachment structure was set on an air-bearing sled to permit relocation of the PFR to one of six locations used to vary the location of the feet relative to the ODS. This manipulation is relevant to ORU placement at an EVA work site, and it reveals the effect of PFR placement of mass handling through the constraints it imposes on postural configuration and control. Data from all six positions are combined in the results that are presented in this report.

4. Data Reduction

Our ground-based investigation of EV mass handling combines a scientific approach to human movement with a commitment to operational validity. From the dual grounding in the behavioral sciences and EVA operations emerged a methodology for assessment of mass-handling skill in the PABF. Central to this protocol is the application of anthropomorphically valid measures that relate to detectability and stabilizability in nested human-environment interactions. The measures summarized in this section are relevant to stabilizability insofar as they describe movement variability and some of the factors, within the domain of postural control, that influence movement variability. They are relevant to detectability insofar as they plausibly are observable by human sensory systems. These measures were developed in our prior research, and they have been adapted and validated for the present context of simulated EV mass handling. Eventual on-orbit application of these measures will be facilitated to the extent that they are available with common instruments and are robust to suboptimal non-laboratory conditions.

4.1 Anthropomorphically Valid Measurement Systems

Measurement systems used in the analysis of human-environment interactions should relate to known properties of human perception and action systems and to the goals of the interaction [5]. The meaningfulness of the measurement system should be grounded in the relation between perceivables and control actions. We have developed methods for data analysis that are firmly grounded in *psychophysics* and *neurophysiology.* For example, the choice of sampling rates in our data collection is guided by the bandwidth of the human sensory systems that are sensitive to position and motion of the body. Activity within dimensions of stimulation is summarized or reduced to (temporally) global parameters for data distributions (e.g., location, spread, asymmetry) that are robust to noise or fuzzy observation. These global parameters are "updated" at rates that are based on the bandwidth of the task-relevant action systems.

Such methods are not seen in classical biomechanics because they do not support the interval or ratio scales, the low noise, or high sampling rates that are considered to be necessary for the analysis of mechanical coupling in kinetic chains. Our methods are not motivated by these biomechanical objectives. Instead they are motivated by the need to understand *informational coupling in a chain of control subsystems* [1, 2, 13]. As with the human nervous system, this frees us to exploit the robust information in fuzzy observations, it considerably relaxes the requirements of our sensors (or scientific instrumentation), and it places the burden on flexible task-specific post-processing.

Our approach to extravehicular mass handling focuses on whole-body coordination. Such coordination should be revealed in the operations or relations of the measurement system [26]. The key parameters in our measurement system include upper- and lower-body angles and either kinematic or kinetic evaluation functions for these configurations. We have found the associated postural configuration spaces to be useful in a variety of situations [1-6, 13]. Our methods rely heavily on graphical description of multidimensional relations within and across sets of configuration spaces, as is common in *exploratory data analysis* and *scientific visualization* of complex phenomena. We used orthogonal axes to represent coordination and control; however, we do not assume Euclidean or any other metric geometry. This is prudent because there is no reason to believe that the concatenation of perceptual "dimensions" follows Euclidean conventions [27]. We assume that the relationship between perceptual sensitivity and "objectively" measured dimensions is monotonic but not necessarily linear [4, 5, 28]. Thus, we consider the *topologically invariant patterns* that emerge in these configuration spaces to be fundamental. This is critical because only topological features would be invariant over changes in the response characteristics or dynamics of the perception and action systems (e.g., adaptation and fatigue). We believe that the resulting methods of data analysis and representation, along with the associated measurement system, provide the most anthropomorphically valid approach to the analysis of human movement and skill. As with human skill, this approach is adaptable to a wide range of situations including those that approach the limits of observability (e.g., measurement and evaluation in noisy or impoverished conditions).

4.2 Summary Statistics Used in Time-Scale Reduction

The most novel aspect of data reduction in this investigation can be described as a reduction of time scale. The sampling rate for the raw data-channels is reduced, by an order of magnitude or more, by computing ordinary summary statistics over successive intervals in the raw data. The reduced data sets are time-histories for various summary statistics. Time series for summary statistics are not unusual in the behavioral sciences. They are most often seen or evaluated as changes or trends over successive sampling periods, such as sessions, days, or even experiments. Such trends are most informative when they summarize changes or trends in the characteristics of data distributions. Distributional characteristics such as spread and asymmetry provide statistically diagnostic information such as the reliability and representativeness, respectively, of common estimates for defining characteristics such as the central tendency of a distribution. The various characteristics of a data distribution provide insight into the underlying "environment" in which the data were collected or into the nature of the process from which the data were collected. Changes in characteristics of a data distribution suggest changes in that which is generating the data.

A scientist attempts to understand something about a data-generating process or system by probing it with experimental manipulations or inputs. Hypotheses are tested and models are constructed by comparing the experimentally observed outputs to the inputs. Such analyses must take into consideration the fact that change in the outputs can result from changes in the inputs or from changes in the intervening system. Systemic changes are suggested by changes in the distributional characteristics of outputs when the experimental conditions and inputs are relatively constant. Under such conditions, increases in the spread of an output distribution suggest a decrease in stability of the system, and increases in asymmetry suggest a departure from equilibrium [1, 3]. These guidelines are as relevant and valid for observation of oneself as they are for observations by an external observer. The premise of our time-scale reduction is that *individuals can pick up information about the dynamics of their own bodies through observation of the distributional characteristics of their own movements.*

We do not make the assumption that there is conscious awareness of these distributional characteristics or of dynamics, as such. Consider an analogy to the auditory system. We are not aware of microscopic temporal characteristics such as the relative location of peaks in the frequency spectrum of a spoken sound, but we are perceptually sensitive to such characteristics and we hear them as one vowel or another. Nor are we aware of the microscopic time delays between noise bursts and ensuing harmonic structure, but we are perceptually sensitive to such characteristics and we hear them as one type of consonant or another. Similarly we assume that vestibular and somatosensory systems (and to a lesser extent, the visual system) are sensitive to rapid or high-frequency patterns in body motion, and we assume that they are perceived as an exigency for a particular control strategy and body configuration. The most important exigencies for motor control are stability and equilibrium [5]. We thus expect body configuration and controlled movement to be systematically related to patterns of spread and asymmetry in subtle fluctuations of the body and body movement [1, 3, 6].

Our choices of sampling rates in data collection and update rates in data reduction are based on known characteristics of human perception and movement. During mass handling, forces and torques are generated against support surfaces and the body of the mass handler experiences subtle accelerations. We measured these interactions with force/torque sensitive platforms and accelerometers. The same events that are registered by these sensors also stimulate the sensory systems that are sensitive to the mechanical consequences of motion (e.g., semicircular canals, muscle spindles, and cutaneous receptors). These sensory systems are sensitive to fluctuations in force and motion up to frequencies of several hundred cycles per second [29-31]. Setting the sampling rate of our data collection at 500 Hz allows us to measure fluctuations that plausibly can be represented in neural activity (i.e., presumably are observable by the human sensory systems).

Patterns in these fluctuations, such as spread and asymmetry, become defined over intervals of time. The rate at which the patterns are observable should be based on the bandwidth of the control actions to which they are linked. Our investigation focuses on postural control. Postural control, based on a linear relationship between postural inputs and outputs, occurs predominantly at frequencies below 1 Hz [32, 33]. Setting the update rate of our data collection at 2 Hz allows us to measure patterns in fluctuations at a rate that is about as fast as this information can be used for postural control (Figure 3). Spread is operationally defined as the standard deviation of key postural parameters within a 0.5-sec (second) interval (e.g., 250 data points for force, moments and acceleration). Asymmetry is operationally defined as the skewness of the 0.5-sec data distributions. Interpretation of these statistical moments is facilitated by removing trends or relatively slow drift in the movement. This is important insofar as some of our data are from systematic changes in position rather than from zero-mean processes. A simple way to detrend the data is to express each observation as a difference from the preceding observation. Detrending and computation of these statistical moments are standard procedures in the physical and behavior sciences.

4.3 Variables in the Reduced Data Sets

The "primary" data sets that are derived from the raw time histories for the data collected in the mass-handling experiments are conceptualized as bundles of variables that take into account the data-collection device (i.e., force plate, accelerometer, video) and the hypothetically important observables (i.e., ORU control, postural configuration, postural stability). The interrelationship of transducer and observable is depicted in Figure 4. All variables in the reduced data sets are transformations or summaries of the data channels in the raw time-history files. As explained in Section 4.2, particular summary statistics are computed from intervals of data in the raw time-histories. Each reduced variable is a time-history specified at a 2-Hz update rate. Each data point in the reduced data sets is determined through computation of a summary statistic over a 0.5-sec interval from the corresponding detrended raw time-histories. The number of data points from which these summaries are calculated depend on the sampling rate in the raw time-history (e.g., summaries are based on 250 data points when the sampling rate is 500 Hz).

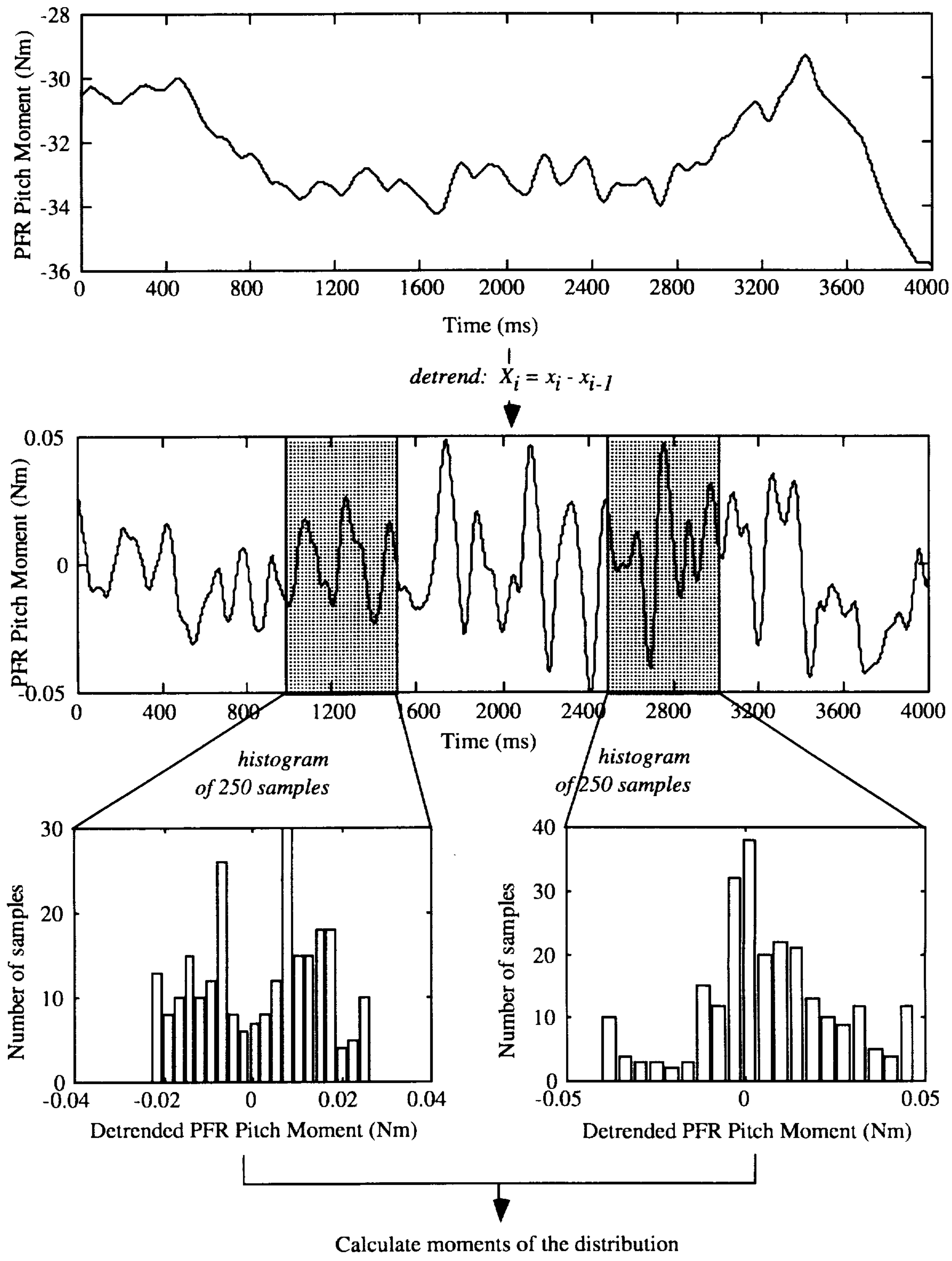

Figure 3: Data reduction procedure to 2-Hz update rate.

4.3.1 ORU Control

The task of the subject was to transport and dock the ORU. Operationally, smoothness of motion and subtlety of control is critical to successful performance in such EVA tasks. Smoothness of force and motion time-histories was revealed by the spread of data within an interval (see [12] for detail). Only data on the smoothness of ORU motion are presented in this report. Smoothness was summarized by computing the standard deviation on the detrended videographic data within each 0.5-sec update interval. Videographic data on the position of three corners of the ORU were sampled at 60 Hz. The within update standard deviations for the corner positions were pooled in the measure of smoothness. The reduced time-histories for smoothness of ORU motion were used in assessing the relationship between postural control and manual control.

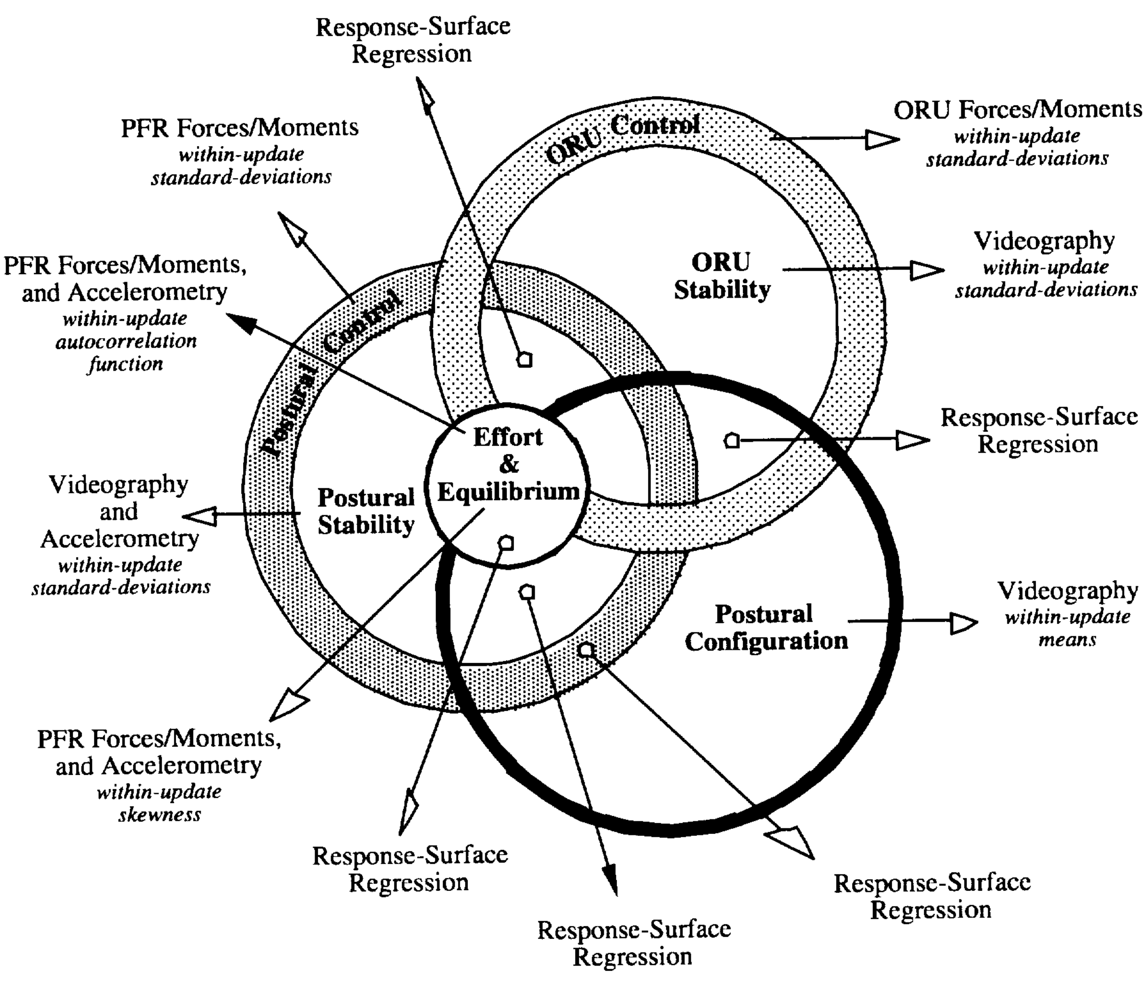

Figure 4: Methodology for investigating nested postural systems and mass handling.

4.3.2 Postural Configuration

Upper-body orientation and lower-body orientation were measured videographically at sampling rates of 60 Hz (see [12] for detail). The mean upper- and lower-body orientation (i.e., postural configuration) was computed within each 0.5-sec update interval. Changes in postural configuration thus were evaluated on a reduced time scale (i.e., 2 Hz). This allowed for a point-by-point comparison between postural configuration and various derived indices of postural stability, postural equilibrium, and manual control. The relationships between postural configuration and these indices reveal the way in which these indices are used or can be used as criteria for control of postural configuration [1]. Analyses focus on body configuration in the sagittal plane (i.e., pitch angles of the upper and lower body).

4.3.3 Postural Stability

Postural stability can be considered as the smoothness of relevant force and motion time-histories and, as such, it can be revealed by the spread of data within an interval. Smoothness can be summarized by computing the standard deviation on the detrended data within an interval. Stability of the body-as-a-whole can be assessed in terms of the standard deviation of the detrended center-of-pressure and any of the forces or torques applied to the PFR (i.e. the force plate), all of which were sampled at 500 Hz (see [12] for detail). These parameters were computed over the same intervals as other derived measures and, thus, they were reduced to the same (2 Hz) time scale. This allowed for a point-by-point comparison between postural stability and various derived indices of manual control and postural configuration. The relationships between postural stability and manual control indicate the importance of stability of the whole body during mass handling. Only force-plate data on sagittal torque are presented in this report.

We have argued that manual control, and even oculomotor control, ultimately must be coordinated with postural control [1, 6]. In particular, it is important to evaluate stability at the shoulder insofar as this region of the body provides the base of support for the head and arms. Stability of posture in the sagittal plane (anterior posterior and superior-inferior axes) was assessed in terms of the standard deviation of the detrended position of the shoulder as indicated in the videographic data. Sagittal stability also was assessed in terms of the standard deviation of shoulder acceleration measured with accelerometers [3]. Data were sampled at 500 Hz from accelerometers mounted on the YAC at bilaterally symmetric locations relative to the longitudinal axis of the EMU (see [12] for detail). Yaw stability was evaluated in terms of the relationship between the anterior posterior data from the two accelerometers. These parameters were reduced to the 2-Hz time scale. This allows for a point-by-point comparison between postural stability and various derived indices of manual control and postural configuration. The relationships between postural stability and manual control indicate the importance of a stable base of support for the arms during mass handling. Analyses focus on postural stability in the anterior-posterior and yaw axes. Particular attention is given to interactions between these axes, that is, in terms of concurrent motion and instability at these axes. Only kinematic data on a-p (anterior-posterior) and yaw acceleration are presented in this report.

4.3.4 Equilibrium

Higher-order statistical moments (e.g., skewness) were computed for the same detrended data on which the standard deviation are computed. Skewness can be used as a measure of departure from equilibrium [3, 6, 7]. This statistic was computed over the same intervals as other derived measures. This allows for a point-by-point comparison between the various indices of postural control. The relationships between postural configuration and skewness of postural control, for example, indicates the way in which such indices are used or can be used as criteria for control of postural configuration [1].

4.3.5 Effortfulness of Postural Control

Enhanced tremor was assessed in terms of the autocorrelation parameters for the detrended accelerometer and force plate data on postural control (see [12] for detail). These statistics were computed over the same intervals as other dependent measures. This allowed for a point by-point comparison between tremor and the various indices of postural and manual control. Relationships between tremor and postural configuration presumably indicate the relative difficulty or effortfulness of various postural configurations [1]. Only data on yaw tremor are presented in this report.

5. Experimental Results

Postural configuration is evaluated with respect to measures for postural stability or ORU stability using response-surface regression. Similarly, postural stability is evaluated with respect to ORU stability using response-surface regression. The quadratic surfaces are based on the following equation (where Z corresponds to an evaluation metric which is represented as the vertical axis is the graph; X and Y correspond to position or motion in orthogonal postural DOF which are represented as horizontal axes in the graph; and the lower-case letters are coefficients in the regression analysis):

$$Z = a + bX + cY + dX^2 + eY^2 + fXY \tag{1}$$

Each regression analysis was done on a batch of data from all trials, including all update intervals within each trial, for a particular subject and a particular combination of restraint condition (postural DOF), ORU trajectory, and docking accuracy. The results summarized in this report are from the four DOF, oblique trajectory, high-accuracy condition from one subject (N=588 update intervals across 12 trials). Combining across trials does not allow us to evaluate any learning within this investigation. In principle, we can derive response surfaces for each trial. These regression analyses would be based on only about 49 data points on the average and, more importantly, they would not include variation in postural configuration that was due to manipulation of PFR position across trials. There were not sufficient resources in this investigation to evaluate change in performance across trials for a particular set of conditions. We felt that it would be more valuable to use multiple trials to explore the effects of postural configuration over a broader range of configurations.

Results from the regression analyses are presented graphically. Statistical assessments are not presented because they are not appropriate for within-subject data. Mathematical statistics do not provide suitable models when the independence of observations cannot be determined. (Most of the quadratic regression fits depicted in this report would be statistically significant, $p<.05$ per comparison, if update intervals were considered to be independent observations.) Consequently, we judge the reliability of our results with respect to replicability in the broader program of research that provides the context for each investigation and each analysis of postural control. This is an important strategy for complicated, expensive, or time-consuming investigations in which one does not have the luxury of testing a sufficiently large sample of (nominally) independent subjects required for powerful statistical inferences.

The scientific-visualization strategy (i.e., response surface regression) reveals the global topological features in relations between the sets of system parameters. Inspection of quadratic-regression surfaces and comparison with distance-weighted-least-squares (DWLS) regression surfaces provides an easily interpretable visualization of the variance that the topological features (i.e., global and local extrema) account for. It is our conjecture that these topological features are dynamical "landmarks" with respect to which posture can be controlled even when, as with most perceiveables in realistic conditions, they are embedded in noise (i.e., uncertainty or more complex patterns). They provide a causal basis for the task-relevant control of posture. The causal relationships are represented in Figure 4.

In the context of postural configuration, note that equation 1 can be re-written as follows

$$Z = (X + k_1 Y + k_2)^2 + k_3(X - k_4 Y + k_5)^2 \qquad (2)$$

where Z is an evaluation metric

X is a lower-body angle

Y is an upper-body angle

$X + k_1 Y + k_2$ is an effect of body lean relatively to a reference orientation

$X - k_4 Y + k_5$ is an effect of body bend relatively to a reference configuration

k_1 is the relative role of upper- and lower-body angles with respect to the effect of body lean

k_3 is the relative role of body lean and body bend

k_4 is the relative role of upper- and lower-body angles with respect to the effect of body bend

k_2 and k_5 are regression coefficients without any special meaning

The results presented in this report do not allow us to determine all these constants and the associated effects of postural configuration on particular evaluation metrics. We will be able to make some inferences about the relative effects of body bend and lean by evaluating the sign and relative magnitude of the coefficient for the (XY) interaction term in our regression analyses. In the mass-handling task, the role played by bend and lean presumably is due largely to the their relative effects on shoulder position with respect to the docking work space. Further insight into these aspects of postural configuration will result from comparison of the three-DOF and zero-DOF conditions insofar as the latter provides unconfounded data on ORU controllability within the reach envelope of the EMU.

5.1 Data Transformations

All the data on ORU control, postural stability, and postural equilibrium had to be transformed to obtain a symmetrical distribution and to homogenize variance in each variable with respect to other variables (i.e., homoscedasticity). The simplest and most common forms of control would be characterized by symmetrical variation in the controlled variable. In addition, symmetry of the data distribution and homoscedasticity in the joint distributions is necessary for subsequent regression relations to be representative (e.g., unbiased by undue influence of extreme values).

It is important to note that the data distributions were symmetrized with a transformation that is typical of transduction of physical energy to neural activity in human sensory systems (e.g., power transformations or, more specifically, logarithmic transformations) and that is typical of relations between physical energy and psychological states (i.e., sensory experience). Such transformations also are common and well-understood in mathematical statistics, especially in preparing data for multiple-regression analyses. The log2 transformation is close to the optimal transformation for symmetry in this data set. It was used because it results in scales that are easy to interpret insofar as equal intervals represent a doubling of magnitude.

5.2 Interaction Between Upper-Body Perturbations With Respect to ORU Stability

Crew members have emphasized the importance of minimizing or otherwise controlling "cross coupling" forces at the ORU during EV mass handling. They have not specifically addressed such cross coupling in the context of stabilizing the body, although they independently have emphasized the importance of body stability. We believe that managing cross coupling during EV postural control is an important, albeit tacit, component of EVA skill. Furthermore, we believe that such forces and motions are sufficiently subtle to be either damped out in ground-based simulators (e.g., Neutral Buoyancy Laboratory) that allow EMU motion in orthogonal body planes (e.g., sagittal and horizontal) or precluded entirely in other simulators (e.g., PABF). If we are correct, there would be little or no opportunity to learn this component of EVA skill on the ground.

We modified the PABF to allow EMU motion in the horizontal as well as the sagittal body planes. Our results show that such multiaxis postural motion is generated during a reasonably high-fidelity simulation of EV mass handling. The results also show that postural stability in each axis influences the smoothness of ORU motion (Figure 5). The quadratic model accounts for 2.2% of the variance in smoothness of ORU motion. The multidimensional relations show that postural perturbations are task-relevant. Moreover, there is an interaction between the orthogonal planes of postural perturbations. The interaction is such that it would be impossible to predict the effect of a pitch-axis (or a-p) perturbation on ORU motion without knowing the magnitude of concurrent yaw-axis motion. Note that the effect on ORU motion increases with the magnitude of pitch-axis perturbation for relatively small magnitudes of yaw-perturbation, but decreases with the magnitude of pitch-axis perturbation for relatively large magnitudes of yaw-perturbation.

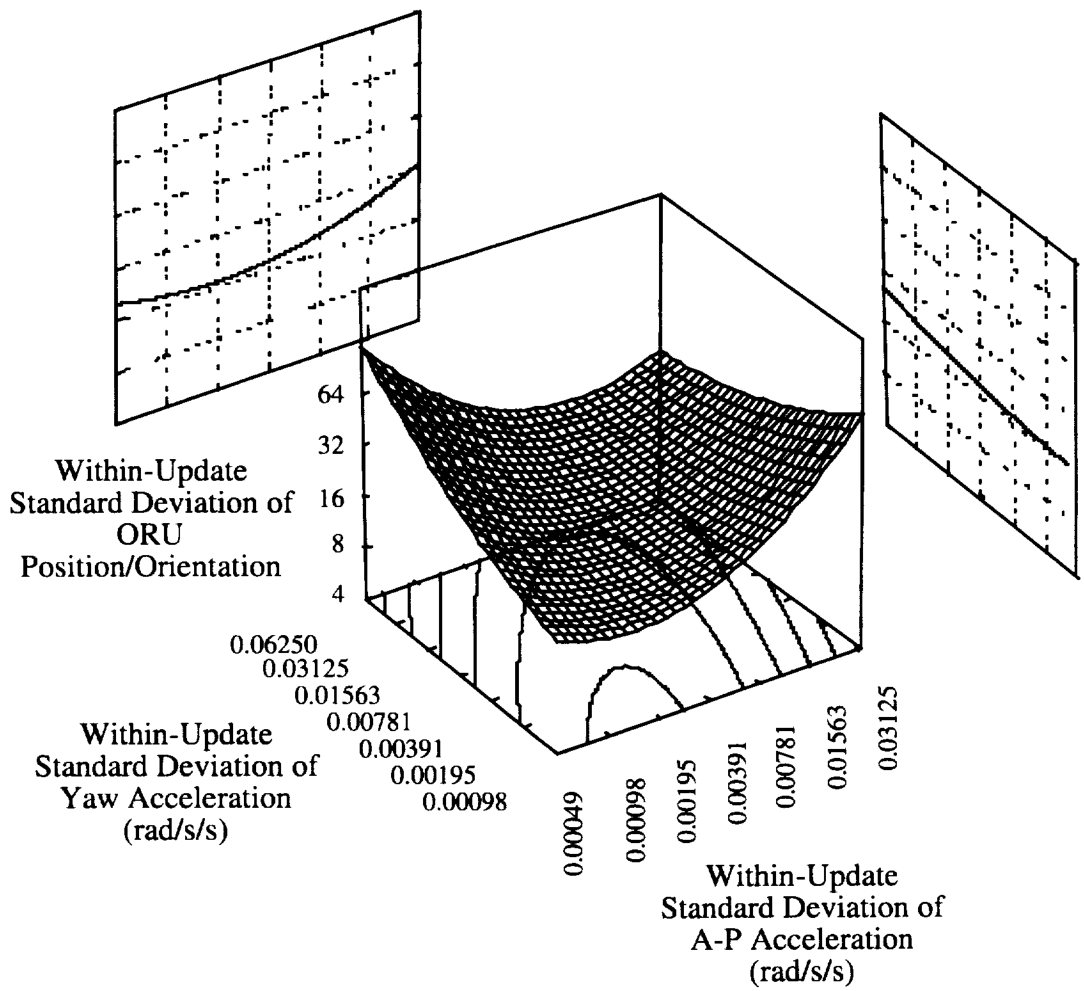

Figure 5: Interaction between upper-body accelerations with respect to smoothness of orbital replacement unit motion.

The operational relevance of such results is not so much that we, as scientists or engineers, need a ground-based simulator within which we can more accurately estimate body stability and its effects on ORU control. These results are important because they reveal subtle patterns of body motion along with their task-relevant consequences that cannot be experienced in extant ground-based simulators. Based on our previous research on a variety of whole-body skills, and based on crew member comments about this specific skill, we believe it is reasonable to assume that observation and control of these subtle patterns and their consequences is an essential and largely tacit component of EV mass-handling skill. It follows that improvements in simulator fidelity and in understanding the implications of crew member comments can be achieved through the application of novel analyses that are motivated by idiosyncratic operational conditions and that draw on established methods in the behavioral sciences.

5.3 Body Configuration With Respect to ORU Stability

We have presented theoretical arguments and empirical findings that an essential component of most whole-body skills is control of postural configuration with respect to task-specific evaluation functions. Our results indicate the task-relevant metrics based on manual control can have a well-defined dependence on postural configuration in EV mass handling as in other tasks. This means that postural configuration has consequences for manual control and, thus, that it is reasonable to control postural configuration so as to facilitate manual control.

Control of postural configuration with respect to manual control requires that the effect of the former on the latter is observable. That is to say, the global relationship between postural configuration and manual control should be understood or otherwise instantiated in the "controller dynamics." On the basis of prior research, we believe that this relationship is understood, albeit tacitly, and that it is instantiated in the whole-body coordination that is an essential part of such skills. Our prior research indicates that minimax solutions on these "surfaces" are achieved through subtle exploratory behavior. Such solutions often seek a saddle region within which postural configuration has a relatively beneficial effect on task performance but within which stimulation due to postural instability (or variability) is sufficiently salient to allow observation of the underlying dynamics (e.g., surface form and gradients).

Quadratic response-surface regression was used to describe the empirical data such as the relations between postural configuration and smoothness of ORU control (Figure 6A). The quadratic model for postural configuration accounts for 5.3% of the variance in smoothness of ORU motion. The topological features of the resulting response surfaces would support the minimax solutions which we have hypothesized to be a mechanism for skilled interactions with the surroundings. We also used DWLS regression to describe, at a finer level of detail, variations from the simple topological patterns otherwise described by quadratic regression (Figure 6A).

Global patterns such as saddles or bowls in the DWLS surfaces could be conceptualized as "signal" while other, more local, variations could be conceptualized as "noise" for perception of the task-relevant postural dynamics and for perception of one's own state relative to such dynamics. From this perspective, global patterns that account for 1% of the variance would correspond to signal-to-noise ratios of approximately -20 dB. Global patterns that account for 10% of the variance would correspond to signal-to-noise (S/N) ratios of approximately -10 dB. By way of analogy, it is interesting to note that the threshold for visibility of objects (global patterns) in veiling illumination or in scattering media is approximately -20 dB S/N [34]. The threshold for detection of pure tones in broadband noise also is approximately -20 dB S/N [35].

Our conclusions about the operational relevance of body configuration are similar to our conclusions about multiaxis perturbations. Exposure to these subtle patterns is important for the acquisition of mass-handling skills that are used during EVA. The importance of simulators that provide exposure to such patterns far exceeds the simple magnitude of the effects on mass-handling performance that would be measured in these simulators. Finally, these patterns provide further quantitative data to inform the placement of PFRs or manipulator foot restraints during ISS construction and maintenance.

5.4 Body Configuration With Respect to Upper-Body Yaw Stability

We believe that postural configuration can directly affect manual control proficiency and stability (see e.g., Figure 6A) through the differential mechanical advantage of various joint angles involving or proximate to the shoulder joint, the stability of equilibrium and nonequilibrium states in the associated agonist-antagonist muscle groups, and through less well-understood micro-biomechanical and physiological properties. We believe that postural configuration also can effect manual control indirectly through its effect on postural stability (e.g., stability of the shoulder as a point in the work space). Figure 6B shows the relationship between postural stability in yaw and postural configuration. The quadratic model for postural configuration accounts for 0.8% of the variance in shoulder yaw acceleration. This is a relatively small proportion of variance but, given the task-relevant interaction between yaw and a-p accelerations (see Figure 5), the effect of postural configuration on yaw acceleration may be more important than Figure 6B suggests. The topological features of this relationship could be included in a cost function for control of postural configuration. The effects of yaw acceleration on smoothness of ORU control (Figure 5) indicate that such a cost function would be task-relevant.

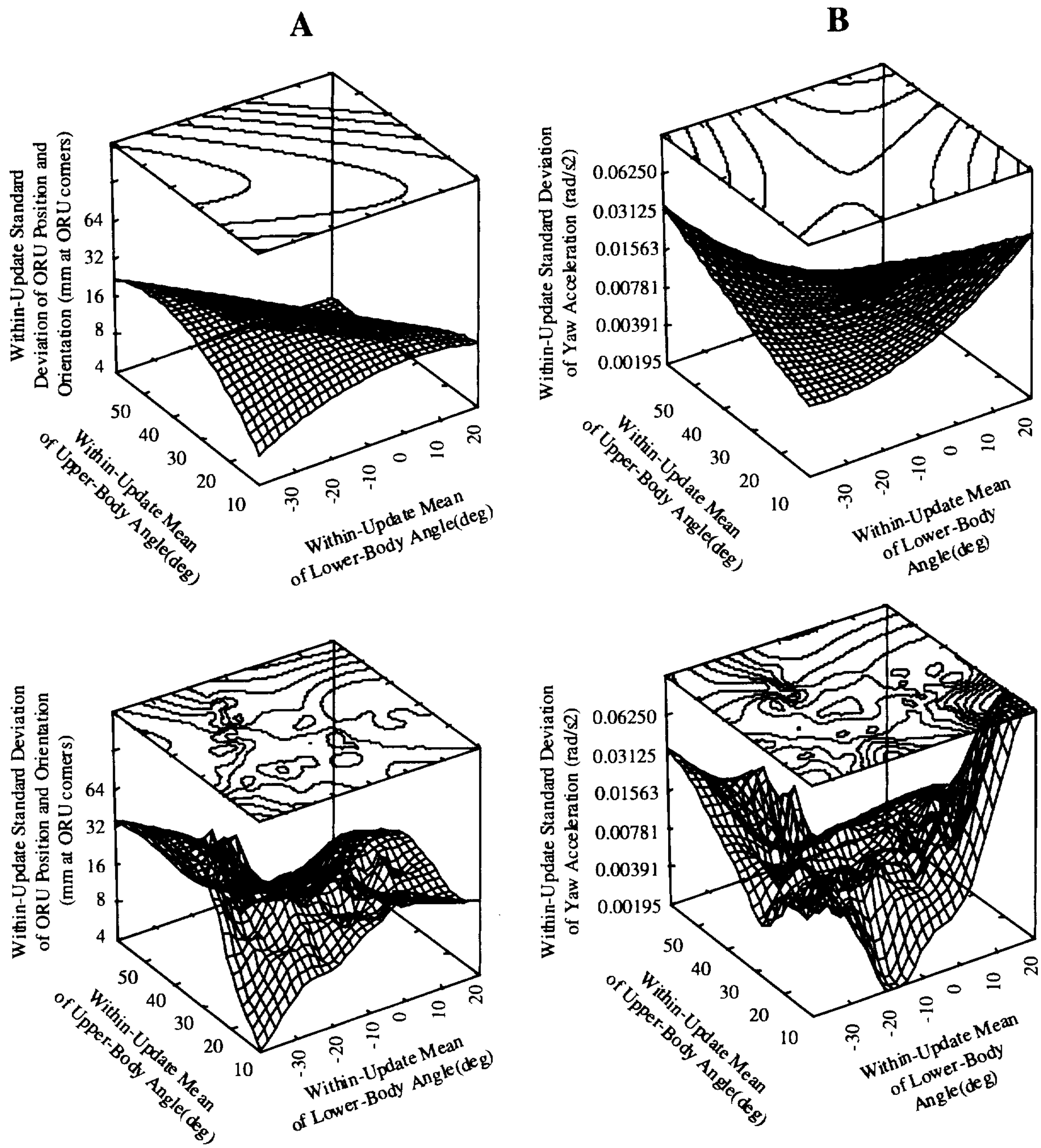

Figure 6: Body configuration with respect to ORU motion (A) and upper-body yaw acceleration (B). Upper panels show quadratic response-surface regression to reveal topological features. Lower panels show distance-weighted least-squares regression to reveal topological "signal" and "noise."

5.5 Body Configuration With Respect to Upper-Body a-p Stability

Figure 7A shows the relationship between a-p postural stability and postural configuration. The quadratic model for postural configuration accounts for 9.2% of the variance in a-p shoulder acceleration. The topological features of this relationship could be included, along with those for yaw stability (Figure 6B), in a cost-function for control of postural configuration. The effects of a-p acceleration on smoothness of ORU control (Figure 5) indicates that such a cost function would be task relevant. Figure 5 also indicates that yaw acceleration would have to be considered concurrently with a-p acceleration in a task-relevant cost function for postural configuration.

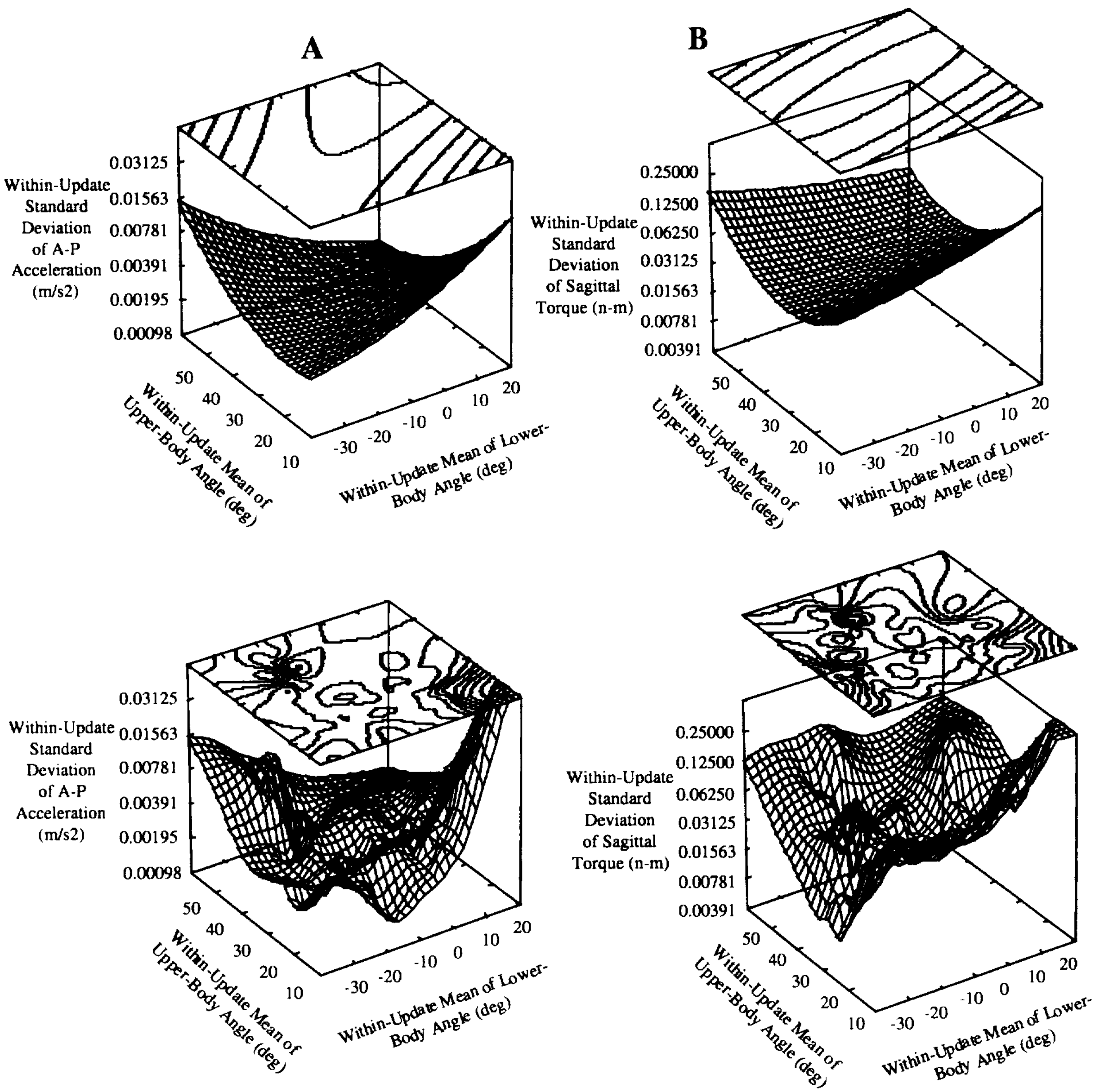

Figure 7: Body configuration with respect to upper-body a-p acceleration (A), and with respect to sagittal torque on the portable foot restraint (B).

5.6 Body Configuration With Respect to Sagittal Stability of Interaction With the PFR

Figure 7B shows the relationship between body configuration and sagittal torque on the PFR. The quadratic model for postural configuration accounts for 7.6% of the variance in sagittal torque. There are two key points about these results: (a) The topological dynamics of postural control can be revealed in kinetic measures as well as in kinematic measures. The significance of this is that there is a wide range of measurement techniques that can be adapted for use in our paradigm which, we believe, is well suited to the definition and measurement of mass-handling skill. (b) There appear to be some differences between the kinematically defined and kinetically defined topologies. Sagittal PFR torque is more sensitive to upper-body angle and less sensitive to lower-body angle than is upper-body a-p acceleration. If this is shown to be a reliable difference, it suggests that postural control (e.g., its cost function) should be influenced concurrently by information from multiple sensory modalities (i.e., somatosensory as well as vestibular or visual systems).

5.7 Body Configuration With Respect to Upper-Body Yaw Equilibrium and Effort

Asymmetry (skewness) is considered as a measure of departure from equilibrium (Figure 8A). The quadratic model for postural configuration accounts for 1.4% of the variance in asymmetry of yaw acceleration. The magnitude of tremor in the 8-12-Hz range is considered as a measure of effort (Figure 8B). The quadratic model for postural configuration accounts for 1.0% of the variance in tremor. Note that the topologies are somewhat similar. This suggests that it is effortful to deviate from a postural configuration that is optimal for mass handling and that it is difficult to maintain such nonoptimal configurations. Nevertheless, crew members may be forced into such configurations by nonoptimal PFR locations/orientations and by poor visibility around or through the ORU. In the lower panel of Figure 8B, the depicted data points and the 50%-probability ellipses are for configurations at "zero" tremor magnitude which are not included in the response-surface regression. Note that no tremor was observed for configurations that otherwise resulted in minimal tremor when it was detectable.

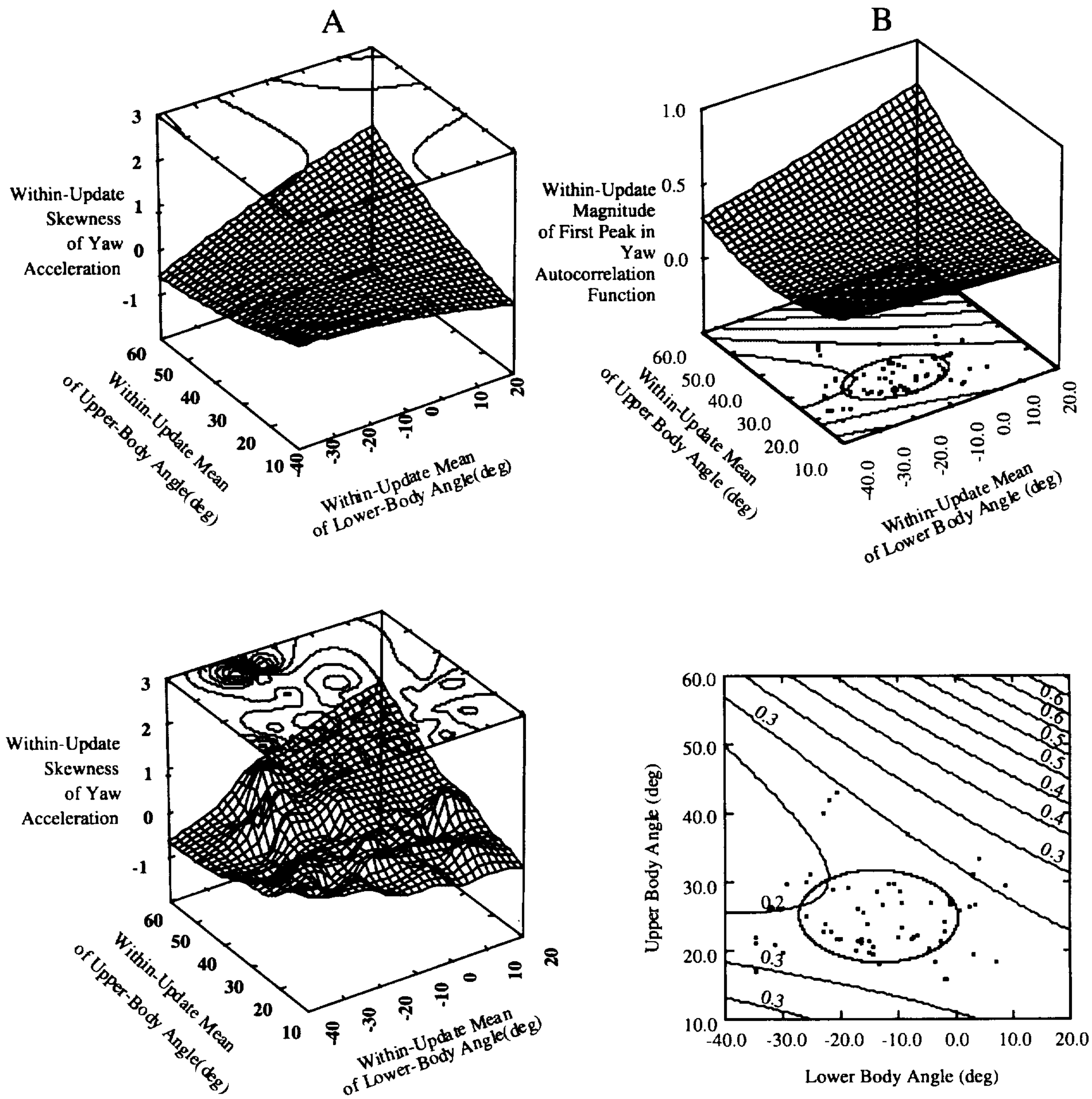

Figure 8: Body configuration with respect to symmetry of upper-body yaw acceleration (A) showing quadratic (upper panel) and distance-weighted least-squares (lower panel) regression surfaces, and body configuration with respect to the magnitude of upper-body yaw tremor (B).

5.8 Transducers for Performance Evaluation

In this study data were acquired using accelerometers, videographic techniques, and force-torque transducers. Each transducer has its own set of strengths, and the constraints of any measurement context may favor the use of one particular transducer. For example, videographic techniques could be more feasible and less intrusive in non-laboratory settings such as on orbit. However, it is important to establish that the transducer chosen is actually sensitive to the measurement parameters of interest. Comparisons of data collected in this study (beyond those presented in this report) using the three different transducers indicated that the topological dynamics of postural control can be revealed with either kinetic measures or kinematic measures. The significance of this is that there is a wide range of measurement techniques that can be adapted for use in a paradigm such as that described here.

6. Conclusions

We have demonstrated that the effects of body stability and body configuration on mass-handling performance can be measured objectively in a ground-based EVA simulator. These effects are consistent with comments of EVA-experienced crew members about the importance of body positioning and stability. Our data suggest that skilled mass handling requires perception of both multiaxis perturbations and subtle motions. We demonstrated that a relatively simple and robust methodology can be used to measure subtle multiaxis perturbations. The methodology can be used to evaluate the fidelity of EVA simulators with respect to such observables, which are important in skilled mass handling. The data from our investigation allow us to explore further the importance of various postural DOF to fidelity of the PABF with respect to EV mass handling. Specifically, we can compare the conditions within which there were three and four postural DOF. Furthermore, evaluation of mass handling in the (nominally) zero-DOF condition allows us to speculate about the value of additional crew member restraints for on-orbit performance [11, 12].

While current ground-based simulators permit exposure to either subtle perturbations or multi-axis motion, there is no opportunity to simultaneously experience subtle multiaxis perturbations. In the course of this project we designed and implemented a multiaxis support system for suited work on the PABF which permits exposure to subtle multiaxis perturbations. The enhanced mass-handling simulator can increase both training efficiency and crew competence. Efficiency is increased by allowing the less expensive and more accessible PABF to be used for training crew sensitivity to these subtle multiaxis perturbations. Activities in the Neutral Buoyancy Lab can then be performed more effectively with attention drawn to aspects of EVA better simulated in that environment. The outcome would be a trained crew member who is better prepared for both scheduled and contingency activities outside the spacecraft (e.g., learning to learn on orbit).

Another important contribution of this investigation is the prospect that a relatively fuzzy concept, such as skill, can be measured objectively. Our data allow us to go considerably beyond the results presented in this report. We intend, for example, to compare response surfaces from subjects with different levels of expertise. In non-EVA tasks, we have seen differences between novices and experts [1]. Response surfaces that are more salient (e.g., quadratic features standing out amid the noise) for experts suggest more consistency and subtlety in coordination of postural configuration with some external system. We also intend to superimpose within-trial and across-trial trajectories for postural configuration (i.e., transition across update intervals) on the response surfaces for the various evaluation metrics (e.g., postural stability/equilibrium/effort, ORU stability). As in prior investigations [1], we expect to see these trajectories tend toward local and global extreme. We also expect to see that the trajectories, in postural configuration space, are concurrently influenced by gradients for multiple evaluation metrics. Such results would be very valuable in the assessment of skill acquisition in ground-based simulators. Moreover, we have reason to believe that such anthropomorphic measures can facilitate communication between novices and experts [1].

The quantitative measures developed in this investigation can be developed further to provide near-real-time feedback about crew member stability and equilibrium during such interactions. Such feedback can be used for rapid prototyping and evaluation of equipment (e.g., suits, restraints) to support advanced EVA. It also could be incorporated into future systems that provide augmented sensory feedback to crew members in the otherwise impoverished sensory conditions of weightlessness or partial gravity. In these more sophisticated technological applications, we expect our techniques to converge with more familiar control-theoretic techniques in human engineering [36, 37]. The convergence will not lead to redundancy, but rather to complementarity, with measures that summarize the timeliness, precision, and operating range of human observation and control of interactions with external systems [2, 15].

The techniques described in this report address configuration spaces while standard control-theoretic techniques focus on state spaces and the implicit energy exchanges in dynamical systems. It should be noted that the distinction between these two sets of techniques should not be confused with the distinction between statics and dynamics. Clearly our techniques reveal important constraints on movement and moveability, but these constraints have as much to do with information as with energy. At present, the relationship between such information (or task) dynamics and the energy exchanges of Lagrangian dynamics is not clear. This simply reflects that fact that we are far from a "physics" of human behavior [1, 17]. A control-theoretic approach to human behavior must transcend, albeit tentatively, the first principles of physics.

7. References

1. Riccio, G. (1993). Information in movement variability about the qualitative dynamics of posture and orientation. In K. Newell (Ed.), Variability and Motor Control, pp. 317-357, Champaign, IL: Human Kinetics.

2. Riccio, G.E. (1995). Coordination of postural control and vehicular control: Implications for multimodal perception and simulation. In Hancock, P., Flach, J. Caird, J. and Vicente, K. (Eds.), Local applications of the ecological approach to human-machine systems, pp. 122-181.

3. Riccio, G., Lee, D., & Martin, E. (1993). Task constraints on postural control. In S.S. Valenti (Ed.), VIIth International Conference on Event Perception and Action, pp. 306-310. Vancouver, Canada: Erlbaum.

4. Riccio, G.E., Martin, E.J., & Stoffregen, T.A. (1992). The role of balance dynamics in the active perception of orientation. Journal of Experimental Psychology: Human Perception and Performance, 18, pp. 624-644.

5. Riccio, G. & Stoffregen, T. (1988). Affordances as constraints on the control of stance. Human Movement Science, 7, pp. 265-300.

6. Riccio, G.E., & Stoffregen, T.A. (1991). An ecological theory of motion sickness and postural instability. Ecological Psychology, 3, pp. 195-240.

7. Stoffregen, T. & Riccio, G. (1988). An ecological theory of orientation and the vestibular system. Psychological Review, 96, pp. 1-12.

8. McDonald, P.V., Oliver, S.K., & Newell, K.M. (1995). Perceptual-motor exploration as a function of biomechanical and task constraints. Acta Psychologica, 88, pp. 127-165.

9. Newell, K.M., Kugler, P.N., Emmerik, R.E.A., van, & McDonald, P.V. (1989). Search strategies and the acquisition of coordination. In S.A. Wallace (Ed.), Perspectives on the coordination of movement, pp. 85-122. Amsterdam: North Holland.

10. Newell, K.M., & McDonald, P.V. (1994). Learning to coordinate redundant biomechanical degrees of freedom. In S. Swinnen, H. Heuer, J. Massion, & P. Casaer (Eds.), Interlimb Coordination: Neural, Dynamical, and Cognitive Constraints, pp. 515-536. New York: Academic Press.

11. Riccio, G.E. McDonald, P.V., Peters, B.T., Layne, C.S., & Bloomberg, J.J. (1997) Understanding Skill in EVA Mass Handling: Part I: Theoretical & Operational Foundations. NASA Technical Paper 3684. Johnson Space Center, Houston, TX.

12. McDonald, P.V., Riccio, G.E., Peters, B.T., Layne, C.S., & Bloomberg, J.J. (1997) Understanding Skill in EVA Mass Handling: Part II: Empirical Investigation. NASA Technical Paper 3684. Johnson Space Center, Houston TX.

13. Riccio, G.E. McDonald, P.V. (1998). Multimodal Perception and Multicriterion Control of Nested Systems: I. Coordination of Postural Control and Vehicular Control. NASA Technical Paper 3703. Johnson Space Center, Houston, TX.

14. McRuer, D., Ashkenas, I., & Graham, D. (1973). Aircraft dynamics and automatic control. Princeton, NJ: Princeton University.

15. Brown, Y.J., Cardullo, F.M., McMillan, G.R., Riccio, G.E., & Sinacori, J.B. (1991). New approaches to motion cuing in flight simulation. Technical Report AL-TR-1991-0139, Wright-Patterson AFB, OH: Armstrong Laboratory.

16. Warren, R. & Riccio, G. (1985). Visual cue dominance hierarchies: implications for simulator design. Transactions of the Society for Automotive Engineering, 6, pp. 937-951.

17. Kugler, P.N. & Turvey, M.T. (1987). Information, natural law, and the self assembly of rhythmical movement: Theoretical and experimental investigations. Hillsdale, NJ: Erlbaum,.

18. Young, L.R. (1984). Perception of the body in space: mechanisms. In I. Smith (Ed.), Handbook of physiology - The nervous system (Vol. 3, pp. 1023-1066). New York: Academic Press.

19. Riccio, G. & Stoffregen, T. (1990). Gravitoinertial force vs the direction of balance in the perception and control of orientation. Psychological Review, 97, pp. 135-137.

20. Zacharkow, D. (1988). Posture: Sitting, standing, chair design, and exercise. Charles C. Thomas, Springfield, IL.

21. Gibson J.J. (1966). The senses considered as perceptual systems. Boston, MA: Houghton Mifflin.

22. Gibson JJ (1979) The ecological approach to visual perception. Boston, MA: Houghton Mifflin.

23. Reed E, Jones R (1982) Reasons for realism: selected essays of James J. Gibson. Hillsdale, NJ: Erlbaum.

24. Canudas de Wit, C.A. (1988). Adaptive control for partially known systems: theory and applications. Amsterdam: Elsevier.

25. Chalam, V.V. (1987). Adaptive control systems: Techniques and applications. New York: Marcel Dekker.

26. Coombs, C.H., Daws, R.M., & Tversky, A. (1970). Mathematical Psychology. Englewoods Cliffs, NJ: Prentice Hall.

27. Garner, W. (1974). The processing of information and structure. New York: Halstead.

28. Stevens, S.S. (1975). Psychophysics: Introduction to its perceptual, neural and, social prospects. New York: Wiley.

29. Howard, I.P. (1986). The vestibular system. In: K.R. Boff, L. Kaufman, & J.P. Thomas (Eds.), Handbook of Perception and Human Performance: I. Sensory Processes and Perception, Ch.11, pp. 1-30.

30. Clark, F.J. & Horch, K.W. (1986). Kinesthesia. In: K.R. Boff, L. Kaufman, & J.P. Thomas (Eds.), Handbook of Perception and Human Performance: I. Sensory Processes and Perception, Ch.13, pp. 1-62.

31. Sherrick, C.E., & Cholewiak, R.W. (1986). Cutaneous sensitivity. In: K.R. Boff, L. Kaufman, & J.P. Thomas (Eds.), Handbook of Perception and Human Performance: I. Sensory Processes and Perception, Ch.12, pp. 1-28.

32. Johansson, R., Magnusson, M., & Akesson, M. (1988). Identification of human postural dynamics. IEEE Transactions on Biomedical Engineering, 35, pp. 858-869.

33. Maki, B.E. (1986). Selection of perturbation parameters for identification of the postural-control system. Medical and Biological Engineering, 24, pp. 561-568.

34. Lythgoe, J.N. (1979). The ecology of vision. Oxford: Clarendon.

35. Dubno, J.R. & Schaefer, A.B. (1991). Frequency selectivity for hearing-impaired and broadband-noise-masked normal listeners. Quarterly Journal of Experimental Psychology, 43A, pp. 543-564.

36. Flach, J.M., Riccio, G.E., McMillan, G.R., & Warren, R. (1986). Psychophysical methods for equating performance between alternative motion simulators, Ergonomics, 29, pp. 1423-1438.

37. Riccio, G.E., Cress, J., & Johnson, W. (1987). The effects of simulator delays on the acquisition of flight control skills: control of heading and altitude. Proceedings of the Human Factors Society - 31st Annual Meeting, pp. 1286-1290. New York, N.Y.: Human Factors Society.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE July 1998	3. REPORT TYPE AND DATES COVERED NASA Technical Paper

4. TITLE AND SUBTITLE
Understanding Skill in EVA Mass Handling: Volume III, Empirical Developments and Conclusions

5. FUNDING NUMBERS

6. AUTHOR(S)
Gary E. Riccio* & P. Vernon McDonald*

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lyndon B. Johnson Space Center
Houston, Texas 77058-3696

8. PERFORMING ORGANIZATION REPORT NUMBERS
S-827

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
TP-1998-3684

11. SUPPLEMENTARY NOTES
* Nascent Technologies

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified/unlimited
Available from the NASA Center for AeroSpace Information (CASI)
7121 Standard
Hanover, MD 21076-1320 (301) 621-0390 Subject Category: 54

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Key attributes of skilled mass handling were identified through an examination of lessons learned by the extravehicular activity operational community. These qualities were translated into measurable quantities. The operational validity of the ground-based investigation was improved by building a device that increased the degrees of freedom of extravehicular mobility unit motion on the Precision Air-Bearing Floor. The results revealed subtle patterns of interac-tion between motions of an orbital replacement unit mockup and mass handler that should be important for effective performance on orbit. The investigation also demonstrated that such patterns can be measured with a variety of common instruments and under imperfect conditions of observation.

14. SUBJECT TERMS	15. NUMBER OF PAGES	16. PRICE CODE
extravehicular activity, mass, orbital replacement unit, control, human factors engineering, man environment interactions	46	

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	None