

Technical Paper 3684



Understanding Skill in EVA Mass Handling

Volume I: Theoretical & Operational Foundations

Gary E. Riccio, P. Vernon McDonald, Brian T. Peters, Charles S. Layne, and
Jacob J. Bloomberg

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Acronyms

ACCESS	assembly concept for construction of erectable space structure
ASEM	assembly of Space Station by EVA methods
DOF	degrees of freedom
DTO	detailed technical objective
EASE	experimental assembly of structures in extravehicular activity
EDFE	Extravehicular Activity Development Flight Experiment
EMU	extravehicular mobility unit
EV	extravehicular
EVA	extravehicular activity
GRO	Gamma Ray Observatory
ISS	International Space Station
LEASAT	Leased Satellite system
LDEF	Long-Duration Exposure Facility
MMU	manned maneuvering unit
ORU	orbital replacement unit
PABF	precision air-bearing floor
PFR	portable foot restraint
PLSS	portable life support system
RMS	remote manipulator system
SMM	Solar Maximum Mission satellite
WETF	Weightless Environment Training Facility
YAC	yaw axis cradle

Preface

This series of four reports will describe the activities performed in the completion of work funded under the NASA Research Announcement 93-OLMSA-07. The funded project, entitled "Environmental Constraints on Postural and Manual Control" was a 3-year project designed to promote a better understanding of the whole-body skill of extravehicular activity (EVA) mass handling. Summary details of task progress can be found in The Life Sciences Division of the NASA Office of Life and Microgravity Sciences "Life Sciences Program Tasks and Bibliography." The Task Book is available via the Internet at: <http://peer1.idi.usra.edu>.

The first report in the series, "Understanding Skill in EVA Mass Handling. Volume I: Theoretical & Operational Foundations," describes the identification of state-of-the-art EVA operational procedures and the development of a systematic and uniquely appropriate scientific foundation for the study of adaptability and skill in extravehicular mass handling.

The second report in the series, "Understanding Skill in EVA Mass Handling. Volume II: Empirical Investigation" describes the implementation and design of a unique experimental protocol involving the use of NASA's principal mass handling simulator, the Precision Air Bearing Floor. A description of the independent variables, dependent variables, methods of analysis, and formal hypotheses is provided.

Volume III in the series presents the data and results of the empirical investigation described in Volume II. The final report in the series, Volume IV, provides a summary of the work performed with a particular emphasis on the operational implications of the phenomena observed in our empirical investigation.

Abstract

This report describes the theoretical and operational foundations for our analysis of skill in extravehicular mass handling. A review of our research on postural control, human-environment interactions, and exploratory behavior in skill acquisition is used to motivate our analysis. This scientific material is presented within the context of operationally valid issues concerning extravehicular mass handling. We describe the development of meaningful empirical measures that are relevant to a special class of nested control systems: manual interactions between an individual and the substantial environment. These measures are incorporated into a unique empirical protocol implemented on NASA's principal mass handling simulator, the precision air-bearing floor, in order to evaluate skill in extravehicular mass handling. We discuss the components of such skill with reference to the relationship between postural configuration and controllability of an orbital replacement unit, the relationship between orbital replacement unit control and postural stability, the relationship between antecedent and consequent movements of an orbital replacement unit, and the relationship between antecedent and consequent postural movements. Finally, we describe our expectations regarding the operational relevance of the empirical results as it pertains to extravehicular activity tools, training, monitoring, and planning.

1. Extravehicular Mass Handling in Context

In this report we will describe the theoretical and operational foundations for our analysis of skill in extravehicular activity (EVA) mass handling. The empirical study of this skill addresses the relationship between postural configuration and orbital replacement unit (ORU) controllability, the relationship between ORU control and postural stability, the relationship between antecedent and consequent ORU movements, and the relationship between antecedent and consequent postural movements. A companion report (Volume II¹) will describe in detail the actual implementation and design of our experimental protocol. On the basis of the outcome of this investigation, we anticipate making recommendations pertaining to crew member training, simulator design and use, on-orbit monitoring of EVA performance, and the use of augmented feedback during on-orbit EVA.

¹ McDonald, Riccio, Peters, Layne & Bloomberg: Understanding skill in EVA mass handling. Volume II: Empirical Investigation

1.1 Skill in EVA Mass Handling

Understanding the skill of extravehicular (EV) mass handling will facilitate planning, mitigate safety concerns, improve training procedures, and enhance simulator fidelity. The nature of EVA is such that it remains one of the most dangerous of all operations during a space mission. The crew are required to physically depart from their spacecraft to perform tasks at or near the limits of their physical capabilities. The challenges faced by EV crew members include:

- reduced visibility as a function of illumination, contrast, field of view and clutter.
- reduced sense of orientation due to inadequate vestibular stimulation.
- reduced proprioception due to inadequate stimulation of the skin, joints, and muscles.
- reduced range of motion due to the extravehicular mobility unit (EMU) limits on the joints.
- compromised strength as a result of fatigue, hardware design, and adaptation to weightlessness.
- reduced body support due to inadequate rigidity, extent, friction, orientation, and location of surfaces.

Given these challenges, successful EV operations are a testament to the adaptability and skill of human operators. Indeed the skill of the human operator has been the keystone to success of many, if not all, 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 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. Some of the new challenges that the EVA operational community will face in the future are listed below:

- Constraints pertaining to International Space Station (ISS) construction will not permit extensive task training. Instead, crew members will need to pursue skill-based training.
- ISS tasks will require crew members to make on-orbit decisions about worksite techniques.
- Simulations of ISS construction will be limited in their fidelity due to the scope of the project.
- ISS crews will not have access to high-fidelity simulators for EVA training and rehearsal.

- ISS activities will increase the number of hours and frequency of EVAs, further burdening current training facilities and procedures.

All these factors could compromise the effective proficiency of the EVA crews. Observations and recommendations of individuals with EVA experience emphasize that this skill is grounded in the management of whole-body stability/mobility and its coordination with manual control:

Training should emphasize the acquisition of knowledge and skills rather than training to a particular set of procedures. Knowledge and skills rather than procedures are what is important when anomalies—particularly those that were never anticipated—occur on-orbit (*EVA Lessons Learned Vol. 2, p. 46*).

Throughout the EVA crew training process, the crew will be trained to limit their motion and momentum so that they are always in control. Training will also include positioning and restraint at the various work sites. Numerous runs in the WETF [Weightless Environment Training Facility] and on the precision air-bearing floor (PABF) will be used to satisfy this objective (*EVA Lessons Learned Vol. 1, p. A-5*)

There are many subtle differences that exist between training in the 1-g world and actual flight activities. Many of these differences can be compensated for in training if the crew members and instructors are aware of the circumstances that lead to these differences and actively participate in correcting them. Some differences, however, cannot be compensated for, but can be kept in mind during training to avoid spurious results and low quality training (*EVA Lessons Learned Vol. 2, p. 5*).

The single greatest distinction between the WETF and the real world is that the EMU is much more stable in the WETF than it is on-orbit. This dynamic instability should be investigated. (STS 54 White Paper, p.17).

Body position and stability is the key, and body restraints are the means. ... Small and large object handling is among several tasks where the differences between the WETF and on-orbit ops can be very significant and are often overlooked (*EVA Lessons Learned Vol. 1, p. 6*).

First and foremost, as with all EVA tasks, body stability and position are essential. The crew member cannot expect to control something else if they cannot control themselves (*EVA Lessons Learned Vol. 1*).

Stable body position is 90% of each task (*EVA Lessons Learned Vol. 2, p.10*).

The goal of the research described in this report is to identify and understand the components of EV mass handling skill by way of controlled testing in ground-based mass handling simulators. This work, by necessity, required the development of measures for the components of this skill. Further, the operational application of this work mandated that we understand the constraints and demands on EV mass handling. The ultimate goal of this effort is to *enhance the skill* level of all

EV crew members, and to facilitate an efficient and safe procedure for training crew in the skilled behavior appropriate for the dynamics of on-orbit EV operations.

Our ground-based investigation emphasizes that skilled mass handling requires the following:

- Sensitivity to postural stability and its implications for manual control
- Sensitivity to the implications of postural mobility for visibility and reach
- Management of the tradeoff between postural stability & mobility
- Control of force couples at the ORU and restraints with respect to the consequences for multi-axis postural perturbations
- Sensitivity to ORU inertia tensor with respect to ORU trajectory, ORU location and orientation, and manual forces

1.2 Shuttle Mission EVAs

A total of 38 EVAs resulting in 453 EVA hours have been performed during the history of the Shuttle program (Table 1). These EVAs can each be classified as one of three types: *scheduled repair/service*, *contingency*, or *detailed technical objective (DTO)*. The repair/service category includes Hubble Space Telescope servicing and repairs and capture of Intelsat-VI. Contingency EVAs have been performed to cope with unexpected events such as the failure of the LEASAT-3's (Leased Satellite system) start sequence (STS-51D), and the failed deployment of the GRO's (Gamma Ray Observatory) antenna (STS-37). The last class, the DTO, has been used to evaluate tools, techniques, and procedures for EVA operations, seen during STS-37, 49, 63, 69, and others. While lessons have been learned from every EVA performed, the DTOs were designed to be specifically informative for the planning/training/performance of future EVA operations, and in particular the construction of a space station. Indeed, STS-61B EVA was specifically designed for evaluation of "experimental assembly of structures in extravehicular activity" (EASE) and "assembly concept for construction of erectable space structure" (ACCESS). The following issues are addressed in these DTOs which comprise approximately 155 hours of EVA:

- Test assembling erectable structures in space (STS-61B, DTO 817).
- Evaluate and verify specific assembly and maintenance tasks for the Space Station (STS-69, DTO 671).
- Conduct a mass handling exercise with the Spartan-204 satellite to gain experience in moving large objects on orbit (STS-63).
- Evaluate several new and some improved spacewalking tools (STS-64, DTO 671).
- Evaluate tools, tethers and a foot restraint platform to increase experience with spacewalks and refine spacewalk training methods (STS-51).

- Evaluate how well spacewalking astronauts can maneuver in weightlessness with a large object (STS-51).
- Better understand the differences between true microgravity and the ground simulations used in training (STS-57).
- Practice moving, aligning, and installing objects with large masses from the end of the robot arm (STS-57).
- Refine training methods for future spacewalks (STS-54).
- Test abilities to move about freely in the cargo bay, climb into foot restraints without using hands, and simulate carrying large objects in the microgravity environment (STS-54).
- Perform an on-orbit demonstration of critical EVA tasks (STS-69).
- Verify the ability to perform tasks that cannot be adequately simulated in ground-based tests (STS-69).
- Provide confidence in EVA interface hardware that has not been used on orbit.
- Verify the ability to perform high-frequency ISS EVA tasks (STS-69).
- Provide data for assessment of the time and effort required for specific EVA tasks (STS-69).

Table 1a. Early EVA Missions

Mission	Dates	EVA Activity	# of EVA/# of Crew/ Total Hours
61-B	11/26-12/3/85	EASE/ACCESS	12 / 2 / 11 13 / 2 / 13.5
51-I	8/27-9/3/85	LEASAT	10 / 2 / 14.5 11 / 2 / 9
51-D	4/12-19/85	Repair Syncom IV satellite	9 / 1 / 3
51-A	11/8-16/84	2 satellite retrievals & recoveries	7 / 2 / 12 8 / 2 / 12
41-G	10/5-13/84		6 / 1 / 3.5
41-C	4/6-13/84	1st repair in space (Solar Maximum Mission satellite), Long-Duration Exposure Facility deployment	4 / 2 / 6 5 / 2 / 6
41-B	2/3-11/84	testing of manned maneuvering unit (MMU) jetpack	2 / 2 / 11 3 / 2 / 12
STS-6	4/4-9/83	First EVA	1 / 2 / 8

Table 1b. Recent EVA Missions

Mission	Dates	EVA Activity	# of EVA/# of Crew/ Total Hours
STS-82	2/11-2/21/97	2nd Hubble repair	34 / 2 / 13.5 35 / 2 / 15 36 / 3 / 14 37 / 2 / 13 38 / 2 / 10.5
*STS-80	11/19-12/7/96	Canceled EVAs	
STS-76	3/22-31/96	DTO 671; DTO 1210	33 / 2 / 12
STS-72	1/11-1/20/96	EDFT-3	31 / 2 / 12 32 / 2 / 14
STS-69	9/7-9/18/95	EDFT-2: DTO 671 DTO 1210	30 / 2 / 13.5
STS-63	2/3-11/95	DTO 671; DTO 1210	29 / 2 / 13
STS-64	9/9-20/94	DTO 671	28 / 2 / 14
STS-61	12/2-13/93	Repair + 1st servicing of Hubble Telescope	23 / 2 / 16 24 / 2 / 13.5 25 / 3 / 14.5 26 / 2 / 13 27 / 2 / 14
STS-51	9/12-22/93	DTO 1210	22 / 2 / 14
STS-57	6/21-7/1/93	DTO 1210	21 / 2 / 12
STS-54	1/13-19/93	DTO 1210	20 / 2 / 9
STS-49	5/7-16/92	Intelsat-VI recovery and redeployment; ASEM (assembly of space station by EVA methods)	16 / 2 / 8 17 / 2 / 11 18 / 3 / 25.5 19 / 2 / 15.5
STS-37	4/5-11/91	EDFE (EVA development flight experiment)	14 / 2 / 9 15 / 2 / 12

* STS 80 EVAs were canceled due to a jammed air lock door.

One may reasonably ask why it is necessary to develop an understanding of the skills involved in EV operations. To some extent we have provided justification on the basis of crew comments (see Section 1.1). However, to date there have been no life-threatening incidents nor have there been any categorical failures in EV operations. It might therefore be easy to claim that EVA is safe and well understood. But there are some factors that should be taken into consideration before making this claim. First of all, not all missions have proceeded as smoothly as initially intended. Perhaps the premier example was the attempted capture of Intelsat-IV during STS-49. The primary capture procedure failed and the mission success rested on an unprecedented 3-man EVA. It was a testament to the skill of the three EVA crew members that the mission was completed without personal injury or loss of the satellite. However, the completion of that mission required the EVA crew members to move closer to the limit of their skills. NASA's operational strategy for avoiding this limit is simply to discourage planning of any EVA activities for which extant EVA equipment and procedures are insufficient and, thus, ensuring the sufficiency of extant equipment and procedures. However, *the probability of an EVA occurring which is at or beyond the bounds of sufficiency will increase substantially with the advent of ISS construction.*

Table 2 shows the per-year breakdown of the 453 hours of Shuttle program EV activity to date. Currently scheduled (3/10/97) EVA hours for Space Station assembly is estimated at 910 hours. On the basis of the 5-year construction period, we will average 182 hours per year. Over the lifetime of the Shuttle program, the peak number of hours in any one year was 106 (1993). For a single mission, the crew has been known to perform 400+ hours training. On average, for each hour of EVA there have been 10 hours of mission-specific training. Based on these figures, each year of ISS construction would require over 1800 hours' training). *Thus ISS construction will require double the number of EVA hours completed in the Shuttle program to date; moreover, it will require these EVA hours be performed in half the time (10 years of Shuttle EVA compared to 5 years ISS construction), and it will exceed the peak yearly hours to date by a minimum of 60%.*

Table 2: EVA Hours per Year

Year	1983	1984	1985	1991	1992	1993	1994	1995	1996	1997	Total
Hours	8	62.5	51	21	60	106	14	26.5	38	66	453

Note that contingency and/or maintenance EVAs, not accounted for in the 910-hours estimate of ISS construction will further increase the total numbers of EVA hours performed over the 5-year construction period. In our opinion, these factors provide reasonable cause for wanting to understand the characteristics of skill during EVA mass handling. The following sections will describe the theoretical and operational foundations which guided our choices in the design of an investigation to achieve such an understanding.

2. Theoretical and Empirical Foundations

Our research on postural control and human-environment interactions (Riccio, 1993a,b, 1995; Riccio, Lee, & Martin, 1993; Riccio, Martin, & Stoffregen, 1992; Riccio & Stoffregen, 1988, 1990, 1991; Stoffregen & Riccio, 1988) and exploratory behavior in skill acquisition (McDonald, Oliver, & Newell, 1995; Newell et al., 1989; Newell & McDonald, 1994) provides a uniquely appropriate scientific foundation for the study of adaptability and skill in EV mass handling. This research has led to the development of meaningful measures that are relevant to a special class of nested control systems: manual interactions between human operators and the substantial environment. These measures are relevant to all such interactions and, at the same time, they are specially sensitive to the peculiarities of weightlessness. This provides for the possibility of co-lateral and synergistic Earth-based and on-orbit research. Fundamental considerations in our systematic program of research are summarized below.

2.1 Unique and General Characteristics of the Approach

Performing visual or manual tasks while sitting, kneeling, or standing is so common that it is taken for granted until there is an obvious problem. Problems can be created by environmental constraints (e.g., workspace design/accessibility, vibration, visibility/illumination, weightlessness), musculoskeletal constraints (e.g., pain, weakness, paralysis, or other neurological disorders), or sensory constraints (e.g., poor vision, dizziness, disorientation, numbness, proprioceptive insensitivity, or other neurological disorders). Problematic constraints are encountered on Earth and in space; and they can lead to unacceptable levels of performance, fatigue, and injury. Many problems can be alleviated through the design of work environments that promote *coordination* between postural control and manual control or at least that allow postural *adaptation* to unusual conditions. Our research, including the ground-based study of EVA described in this report, provides insight into this general process of coordination along with the environmental and biological requirements for the associated skills.

There are many constraints on human performance in EVA that are different in origin but similar in effect to constraints imposed on human performance on Earth:

- Reduced visibility due to inadequate illumination, contrast, and field of view
- Reduced sense of orientation due to inadequate vestibular stimulation
- Reduced proprioceptive sensitivity due to inadequate stimulation of skin, joints and muscles
- Reduced range of motion due to limitations on the joints
- Inadequate strength relative to common task demands
- Reduced support due to inadequate rigidity, extent, friction, orientation, or location of surfaces and restraints
- Inappropriate placement of objects to be seen and handled

We have exploited existing non-EVA research on coordination of postural control and manual control to guide an investigation of human performance in EVA. We expect that an understanding of human performance during EVA can inform us about fundamental postural skills and constraints on their use and adaptability in both terrestrial and nonterrestrial environments.

Most EVA investigations and DTOs have considered the crew member as a mechanical element of an EVA system. Our study provides insight into 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 from the perspective of adaptive control theory.* In this sense, 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 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 are developing an understanding of adaptability that is sufficiently general to extrapolate from research findings or DTO results to new EVA tasks. Our investigation will yield insights that will increase our ability to generalize past investigations and current DTOs and, thus, will facilitate planning for future EVAs that exploit the skills of crew members for whole-body coordination and adaptation.

2.2 Human-Environment Interactions

The human-environment interaction is fundamental to perception and action (Gibson, 1966, 1979). *Perception* and *action* are inseparable aspects of this interaction, and they should not be studied independently. Externally valid investigations that focus on perception must view action in an environment as an important context for perceiving. Research on perception includes the identification of what is perceivable (i.e., information in sensory stimulation). In the context of action, essential information is often an emergent property of an interaction with the environment and, thus, may be available only in the interaction. The pick up of this information allows for the adaptive modification of action and the achievement of particular performance objectives. Externally valid investigations that focus on action must view perception in an environment as a context for action. Research on action includes the identification of what is achievable (i.e., mechanics of movement). In the context of perception, essential movements are often exploratory and these movements make information available about general characteristics of the human-environment interaction (McDonald, Oliver, & Newell, 1995; Newell et al., 1989; Newell & McDonald, 1994). These general characteristics can be exploited in the modification of action or behavioral objectives. In human-environment interactions, perception supports action and action supports perception (Riccio, 1993b).

Perception and action are so fundamentally intertwined that differentiation between these concepts is potentially misleading. It is important to emphasize at the outset that the juxtaposition of these concepts should not imply that they have independent status epistemologically. At the same time, a considerable amount of research in phenomenology, psychophysics, biomechanics, and neurophysiology treats perception and action as if they were separable. Such research constitutes a broader scientific context within which our research is conducted, and it would be unwise to wholly neglect this context. The use of separate terms, perception and action, reflects this context but the juxtaposition of these terms herein connotes their inseparability.

The fact that action has perceivable consequences and that perception allows for the guidance or modification of action means that a human-environment interaction can be conceived as a *closed-loop system* (cf., J. Gibson, 1979, p. 225). The behavior of such systems is modeled mathematically in control-systems engineering. The mathematical techniques used in control-systems engineering are sufficiently diverse (e.g., spanning, in principle, the entire science or sciences of dynamics) that it is difficult to identify the defining characteristics of "control theory." The only common assumptions in control-systems engineering are the coupling between perception and action and the complementariness between a controller and a controlled process. Beyond this, there is a style of analysis and synthesis that is uncompromisingly functionalistic.

This functionalism is characterized by careful consideration of the breadth and depth with which any system is described. Descriptions of system components are commensurate with the task or function of the system which is considered at the outset. There is as much consideration of a system's limits as what it can do within those limits. That is, *a system is described with respect to what it can achieve and with respect to the domain of events with which the achievement is possible.*

2.3 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). In principle, interactions with the environment increase complexity of the human-environment interaction by increasing the number of components or subsystems that must be considered. In fact, constraints that subsystems impose on each other reduce the dimensionality of the interaction and they simplify the control of a complex system (Riccio, 1993b). 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. 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. Partly for pedagogical reasons, we use the lowest dimension possible when describing a particular constraint; however, we address only those constraints that can be generalized to more complex systems and to the class of interactions under investigation. Each low-dimensional approximation is, in this sense, a concrete instance of a primitive for the complex system.

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 dynamic 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 dynamic states and the inputs to subsystems). *Observability and controllability are sufficient but not necessary conditions for all control systems.*

The most important aspects of the human-environment interaction in our investigation of EVA mass handling are the functional consequences that body configuration and stability have for the pick up 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 individual, the environment, and the task (Riccio, 1993a). This general skill suggests that individuals should be sensitive to the *functional consequences* of body configuration and stability. In other words, human operators should perceive the relation between configuration, stability, and perception or action performance so that they can adaptively control their interaction with the surroundings (Riccio & Stoffregen, 1988). In our investigation, we have identified a level of analytical detail that is sufficient to appreciate 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 (Riccio, 1993a,b).

Human-environment interactions can be analyzed in terms of component subsystems. The reduction of a system to subsystems is guided by the relatively autonomous subsets of the scientific community that each can contribute insight to the problem. It also 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 operator meet these criteria as do objects and devices in the physical environment. These nested 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 able to be detected when there is a mapping between these dynamical states and the inputs to the sensors. The system can be stabilized 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 nonlinear systems.*

The strategy outlined above can be used to evaluate facilities and systems that are designed to simulate nonterrestrial conditions and to familiarize individuals with those conditions. It offers a nonarbitrary and anthropomorphic basis for prioritizing the many factors that must be considered in replicating or neglecting attributes of a complex environment. Essential attributes for a high-fidelity simulation are those that relate to the ability to stabilizability and detectability of particular human-environment interactions. Attributes that are required for one task may be unnecessary or incidental to performance on a different task.

This suggests that simulator fidelity is task-specific and that evaluation of fidelity should be selective. Fidelity may be dictated by qualitative correspondence between the simulator and the simulated environment with respect to categories of information and control parameters. Quantitative precision in simulation of complex systems may be relatively unimportant (Warren & Riccio, 1985; Riccio, 1995). Finally, the comprehensiveness 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.

2.4 Information in Movement Variability

Human-environment interactions constitute robust systems. 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. Human operators can tolerate variation in postural states, and such variation can serve an important function in adaptive systems. Postural variability generates stimulation which is "textured" by the dynamics of the human-environment system (Riccio & Stoffregen, 1991; Riccio, 1993a,b). 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 (Canudas de wit, 1988; Chalam, 1987; Narendra, 1986). 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.

Riccio (1993a) 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 pick up 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. In addition, if patterns are more salient in particular regions of the state space (e.g., for particular orientations or configurations) it may be adaptive to occupy or tend towards these regions even if they do not contain the most energy-efficient states.

Evidence for systematic bias away from energy minima has been obtained in diverse experiments on human movement (Riccio, Martin, & Stoffregen, 1988; Beek, Turvey, & Schmidt, 1992). In these experiments, systematic bias apparently improved the observability of system states. Such considerations emphasize that informativeness and controllability of movement variability should be included in models of human-movement systems.

Riccio (1993a) 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 (Riccio & Stoffregen, 1988). 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 (Figure 1). "Response surface" manifolds described the relationship between configuration and either stability or equilibrium. The manifolds were derived using Distance-Weighted Least-Squares Regression. Variability of force was increased by bending and decreased by leaning.

The relationship 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 apparently required more variability in order to perceive symmetry.*

2.5 Coordination of Postural Control and Manual Control

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 a 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 for:

- looking at, around, and through
- touching, reaching around, or reaching through
- 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 (Ricchio & Stoffregen, 1991). *Thus, visual or manual control performance provides evaluation functions for postural configuration.*

Ricchio (1993a) 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 of about 3 times per second and with constant force on a force-sensitive electronic keyboard. The electronic keyboard provide auditory feedback about the forcefulness of tapping. The subject was instructed to maintain a variety of particular postural configurations (i.e., upper- and lower-body angles) which were measured goniometrically and displayed schematically in real time. Figure 2 shows the relations between postural configuration and either variability of tapping force or variability of intervals between taps. The 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 due to 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 to falling in (from) these configurations. 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, and it reveals the multicriterion control that is a basic characteristic of the coordination of postural control and manual control (Ricchio, 1993b). 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 (Ricchio & Stoffregen, 1988). 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 workload in various perceptual-motor tasks (Ricchio, 1993a). 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 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*.

The postural effects described above emphasize the importance of task or informational constraints on action systems vis-a-vis purely mechanical constraints. Task constraints are a general property of human interactions (Ricchio & Stoffregen, 1988). The surroundings of a human action system can be the surfaces, media, and objects in the "natural" environment; human artifacts in the "modified" environment; or other systems or components of the human body. A superordinate system is formed when an action system is coupled with aspects of its surroundings, and this superordinate system may be capable of achieving goals that cannot be achieved with any of the component subsystems (Ricchio, 1993b). These superordinate goals do not necessarily replace the goals or functions of the subsystems. Instead the goals and systems become nested: the goal-directed behavior of the system constrains the way in which the goals of a component subsystem can be achieved, and vice versa. While the goal-directed behavior of a system imposes such constraints on the behavior of component subsystems, the associated coupling among subsystems affords opportunities that may not be possible without the coupling. Intentional systems presumably perceive and act upon these affordances by adaptively coupling with their surroundings in ways that are consistent with the attendant opportunities.

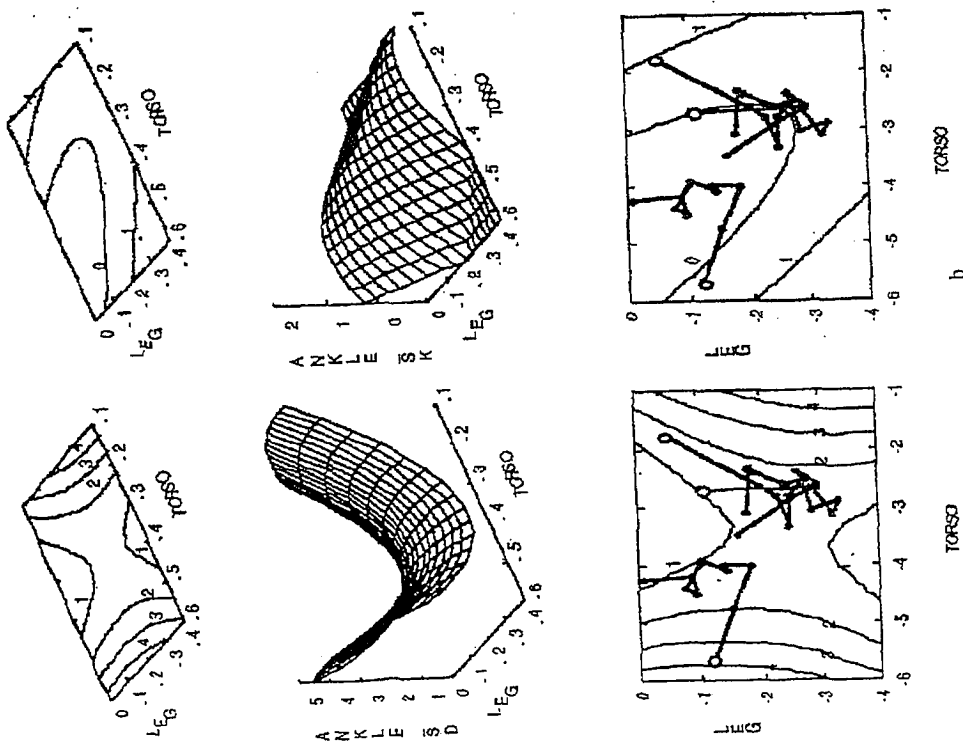


Figure 1. Quadratic response surfaces that describe how postural configuration influences movement variability (a) and symmetry (b). Isovariability and isosymmetry contours are also presented. Trajectories for each 10s trial arc represented in the lower contour plots. Open circle denotes initial configuration; negative numbers indicate posterior tilt of body segment. (Figures 1&2 were originally published in Riccio, 1993a)

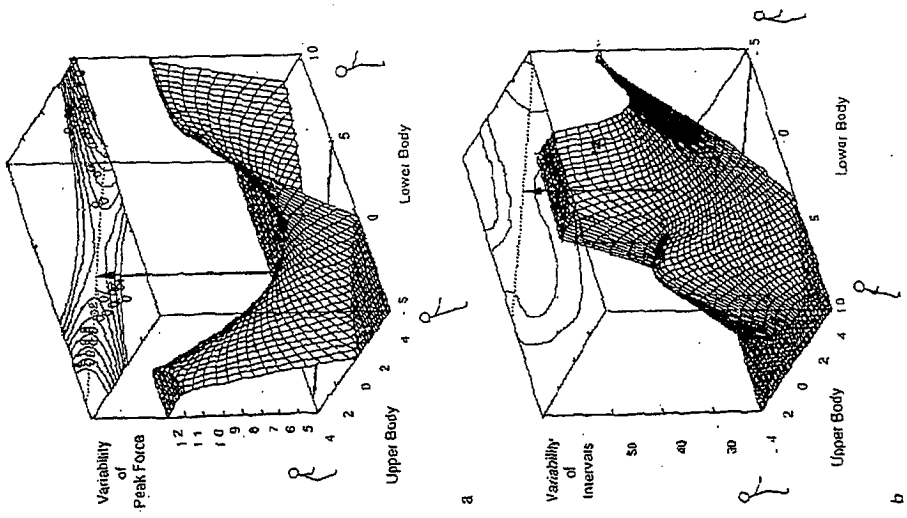


Figure 2. Task-relevant postural spaces for performance on the constant-force interval-production task. The vertical axis represents the coefficient of variation for peak force (a) and for intervals between taps (b). Numbers on other axes indicate degrees from vertical. Response surfaces represent the influence of orientation and configuration on performance. The surface in (a) is derived from quadratic regression. The surface in (b) is derived from DWLS regression because the quadratic fit was inadequate. Iso-performance contours are also represented. The bold arrow represents erect stance.

3. Experimental Design and Data Reduction

Our ground-based investigation of EV mass handling combines the scientific approach, summarized above, with a commitment to operational validity (McDonald, et al., 1995, 1996, 1997). From the dual grounding in the behavioral sciences and EVA operations emerged a unique empirical protocol implemented on NASA's principal mass handling simulator, the PABF. Central to this protocol is the application of meaningful measures for detection and stabilization in nested human-environment interactions. Measures developed in our prior research have been adapted and validated for the coordination of postural control and manual control in simulated EV mass handling. On-orbit application of these measures will be facilitated to the extent that they are available with common instruments and are robust to suboptimal nonlaboratory conditions. The suite of measures used in our ground-based investigation are described below.

3.1 Experimental Design

A full description of the experimental design is provided in Volume II. However, this brief description will help put the following material in context. Subjects were suited in a Shuttle EMU, pressurized to 4.3 psi. They were placed in a recumbent orientation, left hand down, and supported by a frame attached to the portable life support system (PLSS). This frame was fitted with bearings located along an axis which ran through the center of mass of the human-EMU system and sat in a "cradle" device so as to permit body yaw rotation—the yaw-axis cradle (YAC). The YAC-EMU assembly was supported on an air bearing sled. The subject's feet were affixed to a foot restraint (PFR) which was attached to a rigid, immovable structure. Thus the subject, restrained at the feet, could pitch and yaw, and translate in the anterior-posterior and superior-inferior axes by virtue of the air bearing sled and the yaw-axis cradle. In this configuration, subjects performed an ORU docking task, maneuvering a 5 DOF (on air bearings) ORU into a docking structure. Trials were repeated with the PFR placed in 6 different locations relative to the docking structure, with varying degrees of freedom permitted for body motion, varying ORU translation trajectories, and under two conditions of docking accuracy. During all of the trials, force and moment data were collected at the PFR and the ORU handle. We also used a video-based tracking system to track the motion of the EMU and the ORU relative to the PFR and the docking structure. Accelerometers were placed on the YAC to detect yaw rotation. Finally, we recorded extensive verbal ratings and comments from the subjects during and after data collection. Subject experience of suited mass handling covered a broad range. Some had experience of activities only on the PABF; others had performed mass handling on the PABF, in the WETF, and on the KC-135 during parabolic flight. We also had one subject with substantial on-orbit EVA experience.

3.2 Operational Constraints on Experimental Design

Our empirical effort was designed to examine mass handling performance as a function of several factors central to on-orbit EVA operations which addressed:

- worksite configuration (manipulations of ORU trajectory and location of the foot restraint)
- type of restraint available (manipulation of the DOF of EMU motion)
- manual precision required (docking accuracy)
- the skill level of the crew member (experienced and inexperienced subjects).

During ISS construction, all of these factors will play a role in defining each EVA operation. For example, there will only be a finite number of PFR sites and, while the remote manipulator system (RMS) offers the benefit of flexible placement for the PFR, there will be potential costs in decisions to use the RMS. In particular, the time required to move the RMS from one end of ISS to the other is in the order of several hours. In addition, the RMS will not have access to certain worksites. When the RMS is not used, crew members will need to determine which restraints system to use—the PFR, the body restraint tether, perhaps both, or none at all. Worksite configuration will also demand that ORUs be transported in less than ideal trajectories relative to the body, and the precision demanded during mass handling will depend on the ORU's function and location (e.g. the Hubble repair mission demanded high accuracy because of the precision required of the instrument to function properly). Finally, the skill level of each crew member will vary; this may be a function of the number of EVAs performed, or indeed a function of being on ISS for several weeks prior to an EVA. Our experimental protocol was carefully constructed to address each of these factors.

3.3 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 (Riccio & Stoffregen, 1988). 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. Sampling rates are assessed with respect to the bandwidth of various sensory systems or the bandwidth for specific dimensions of sensitivity within each sensory system. 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 (see, e.g., section 2.3.4). 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* (Riccio, 1993b, 1995). 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 EV mass handling focuses on whole-body coordination. Such coordination should be revealed in the operations or relationships of the measurement system (Coombs, Dawes, & Tversky, 1970). 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 (Riccio & Stoffregen, 1988, 1991; Riccio, et al., 1992; Riccio, 1993a,b; Riccio et al., 1993; Riccio, 1995). 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 (Garner, 1974). We assume that the relationship between perceptual sensitivity and "objectively" measured dimensions is *monotonic but not necessarily linear* (Riccio & Stoffregen, 1988; Riccio, et al. 1992; Stevens, 1975). Thus, we consider the topologically invariant patterns that emerge in these configuration spaces to be fundamental (see, e.g., sections 2.2.3 and 2.2.4). 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 quantitative 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., on-orbit measurement and evaluation).

3.4 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. This is unusual because the result also is a time-history. 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 (Riccio, 1993a, pp. 340-342; Riccio, Lee & Martin, 1993). 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 the kinesthetic perceptual systems 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 (Riccio & Stoffregen, 1988). 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 (Riccio & Stoffregen, 1991, pp. 214-216; Riccio, 1993a, pp. 333-335; Riccio et al., 1993).

Our choices of sampling rates in data collection and update rates in data reduction are not arbitrary. Within the precision of about an octave we can base our sampling rates and update rates on known characteristics of human perception and movement. Kinesthetic mechanoreceptors are sensitive to fluctuations in force and motion up to frequencies of several hundred cycles per second. Discriminating the frequency of kinesthetic stimulation is best at around 50 Hz, falls off rapidly above 200 Hz, and approaches a limit that probably is determined by the range of neural firing rates. 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 kinesthetic 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. The bandwidth of postural control, based on a linear relationship between postural inputs and outputs, is between 1 and 3 Hz. 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. Spread is operationally defined as the standard deviation of key postural parameters defined over the data-points within a 0.5-second interval (e.g., 250 data points for force, moments, and acceleration). Asymmetry will be operationally defined as the skewness of the 0.5-second data distributions. Kurtosis also will be computed as a measure of intermittency of control (Riccio et al., 1993). 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.

Time is not directly relevant to the patterns described above. For such patterns of amplitude distribution, time is relevant only insofar as it defines an interval or batch of data. Time is directly relevant, however, to other patterns in movement fluctuations such as in periodic or cyclical processes. Muscle tremor in general, and postural tremor in particular, are such processes. *Tremor is an inherent property of human movement systems.* It has been hypothesized that enhanced tremor and pathological tremor are signatures of instability in human movement systems (Riccio & Stoffregen, 1991, pp. 216; Riccio, 1993a, pp. 332-333). Evidence for this has been provided by striking periodicities in postural sway observed under conditions that compromise postural control (Martin & Riccio, 1993). We believe that postural tremor can be a useful index of unstable control and fatigue in EVA operations. A simple summary of such patterns is used in our reduced data sets.

Enhanced or pathological tremor is revealed as prominent peaks in frequency spectra for postural motion and as conspicuous periodicities in time-histories of postural motion. Simple autoregressive models are sufficient to describe such patterns. The autocorrelation function, for example, is the correlation of a time series with itself as a function of time-lag introduced between the two series. The lag at which the autocorrelation is maximal indicates (is the inverse of) the frequency of the predominant periodicity, and the magnitude of the correlation at this lag is related to the strength of the periodicity. Identification of the maximal lag is facilitated by removing trends or low-frequency drift in the movement.

3.5 The Matrix of Variables in the Reduced Data Sets

Table 3 describes the origin of the "primary" data sets that are derived from the raw time-histories for the data collected in the mass handling experiments. Volume II contains a complete version of this table, accompanied by a detailed description of each cell. The non-gray cells are those which define a variable to be used in our analyses. The assignment of variables into rows and columns is somewhat arbitrary. The columns in the table can be conceptualized as bundles of variables that take into account the data-collection device (i.e., force plate, video, accelerometer) and the hypothetically important observables (i.e., ORU control, postural configuration, postural stability). All variables in the reduced data sets will be transformations or summaries of the data channels in the raw time-history files. The table rows correspond to particular summary statistics that 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-second interval from the corresponding raw time-histories. The number of data points from which these summaries are calculated depends 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).

Table 3. Matrix of Dependent Variables for the Study of Mass Handling Skill (see text for details)

Primary Data Sets		ORU Control	ORU control	Postural Config.	Postural Stability	Postural Stability	Postural Stability	Force Couples
2Hz Summary		Kinetics	Video	Video	Video	Accel.	Kinetics	Combined
		A	B	C	D	E	F	G
mean	1							
s.d.	2							
skewness	3							
kurtosis	4							
correlation magnitude	5							
correlation lag	6							
sum	7							

3.6 Explanation and Justification for Dependent Variables

Column A (ORU control kinetics): A variable representing a summary of the forces and moments measured at the ORU force plate will be derived insofar as it is unnecessary to test ORU-control hypotheses separately on forces and moments. This variable will be monotonically related to the energy in the collision of ORU with the ORU docking structure. Such an energy-related variable is relevant to the effortfulness of the docking and, thus, it is relevant to the task of the subject.

Column B (ORU control kinematics): A summary of the linear and angular displacement between the ORU and a fully docked position will be relevant to the smoothness and accuracy of docking and, thus, it is relevant to the task of the subject. Smoothness of force and motion time-histories is 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. These reduced time-histories will be used in assessing the relationship between postural control and manual control.

Column C (postural configuration kinematics): This variable will describe changes in postural configuration on a reduced time scale (i.e., 2 Hz). This allows for a point-by-point comparison between postural configuration and various derived indices of postural stability, postural equilibrium, and manual control (described below). The relationships between postural configuration and these indices indicate the way in which these indices are used or can be used as criteria for control of postural configuration (Riccio, 1993a, pp. 332-349). Analyses will focus on body configuration in the sagittal plane (i.e., pitch angles of the upper and lower body).

Columns D & E (postural stability kinematics): It has been argued that manual control, and even oculomotor control, ultimately must be coordinated with postural control (Riccio, 1993a, pp. 343-349; Riccio & Stoffregen, 1988). 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. In the context of our task, stability of posture in the sagittal plane (anterior-posterior and superior-inferior axes) can be assessed in terms of the standard deviation of the detrended position of the shoulder as indicated in the videographic data. Sagittal stability also can be assessed in terms of the standard deviation of acceleration of the shoulder as indicated in the accelerometer data (Riccio et al., 1993). Yaw stability can be evaluated in terms of the relationship between the anterior-posterior data from the two accelerometers. These parameters will be computed over the same intervals as other derived measures and, thus, they are reduced to the same (2Hz) 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 will focus on postural stability in the anterior-posterior and yaw axes. Particular attention will be given to interactions between these axes, that is, in terms of concurrent motion and instability at these axes.

Column F (postural stability kinetics): Stability measures will be derived from the center of pressure on the pedal force plate. 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, or related measure, at the pedal force plate (anterior-posterior and medio-lateral axes). These parameters will be computed over the same intervals as other derived measures and, thus, they are reduced to the same (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 stability of the whole body during mass handling. Analyses will focus on postural stability in the anterior-posterior axis.

Column G (force couple dynamics): Measures will be derived which are composite force vectors computed from forces and moments at the two force platforms. One cannot simply compare force-to-force and moment-to-moment between the two locations to assess rigidity or equilibrium. All forces and moments must be reduced to commensurable units to determine, from these data alone, whether the system is in equilibrium. We are striving for a method of comparing forces and moments at two locations in (endpoints of) a distributed system (the human body) because we assume that the human perceptual systems do this in controlling

posture and in coordinating postural control and manual control while interacting with the environment. We assume that a stable postural platform is necessary for effective interactions with the environment (e.g., manual control) and, thus, that the action (including the forces and moments) at the feet and hands must be controlled with respect to the criteria of postural stability. Our strategy of measuring departure from equilibrium in terms of forces and moments at the hands and feet can be viewed as an operational definition of *the observable and meaningful consequences of coupled actions at the hands and feet*. Particular attention is being given to interactions between the two axes of noncoplanarity, that is, concurrent change and instability at these axes. The noncoplanar interactions within the force couple are compared with the multi-axis interactions in postural motion mentioned in the preceding paragraph. We hypothesize noncoplanar couples are especially destabilizing because of their tendency to induce concurrent perturbations in orthogonal axes.

Rows 3 & 4 (higher-order statistical moments): Skewness and kurtosis are computed for the same detrended data on which the standard deviation are computed. Skewness can be used as a measure of departure from equilibrium, while kurtosis can be used as a measure of intermittency of control (Riccio et al, 1993; Riccio & Stoffregen, 1991, pp. 215-216). These statistics are computed over the same intervals as other derived measures and, thus, they are reduced to the same (2Hz) time scale. 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 (Riccio, 1993a, pp. 332-342).

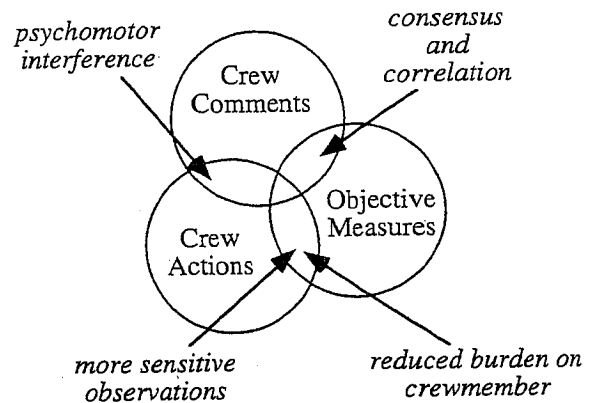
Rows 5 & 6 (autocorrelation parameters): Enhanced or pathological tremor are assessed in terms of the autocorrelation parameters for the detrended kinematic and kinetic data on postural control. These statistics are computed over the same intervals as other dependent measures and, thus, they will be reduced to the same (2Hz) time scale. This allows for a point-by-point comparison between tremor and the various indices of postural and manual control. Relationships between tremor and postural configuration, for example, could indicate something about the relative difficulty or effortfulness of various postural configurations. Analyses will focus on anterior-posterior and yaw axes where available.

4. Operational Implications

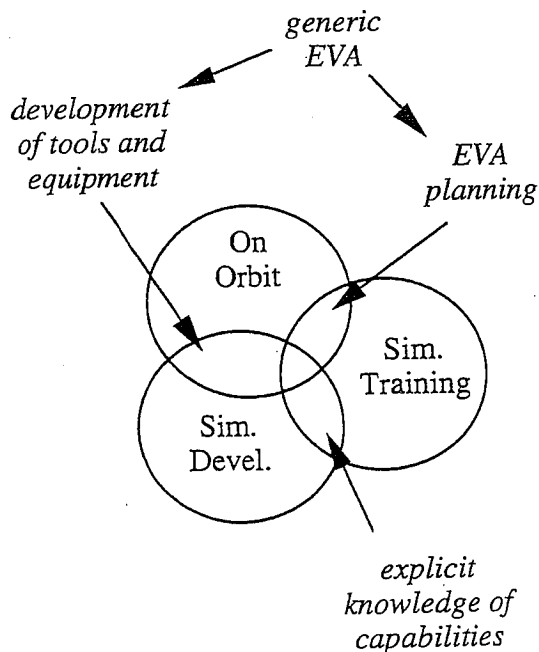
Our mass handling task on the PABF is representative of many EV tasks, even those that do not explicitly involve docking of an ORU. The expected operational implications are schematically summarized below.

Focus and Context for Empirical Effort

- Assess sensitivity to ORU math properties in different restraint systems.
- Assess sensitivity to ORU math properties in EVA training simulators and on orbit.
- Assess effect of various ORU movements on sensitivity to its math properties.
- Assess effect of postural configuration on ORU control.
- Assess effect of ORU control on postural perturbations.
- Assess relationship between subjective evaluations and objective measures.



Operational Relevance of Empirical Information



- Quantitatively elaborate on crew member comments and postmission debriefs about EVA.
- Explicate similarities and differences across crew member comments and postmission debriefs on EVA.
- Expedite crew member self-awareness of capabilities during EVA training.
- Enhance communication between experts and novice crew members about EVA capabilities and limitations.
- Refine understanding of on-orbit needs relative to specifications for EVA tools and equipment.
- Refine understanding of simulator fidelity relative to EVA training and planning.
- Recommend further simulator development relative to EVA training and planning.

We expect the application of knowledge from the PABF investigation to supplement expert opinion about EVA. We expect that such applications can lead to an analytic component of EVA planning and evaluation that can complement the currently extensive, albeit nonanalytic, preparation for and assessment of EVA. Such quantitative analyses can elaborate on the details of EVA events that are otherwise described in written or spoken communication to the extent that time, inclination, and ability permit. These analyses also can reveal or guide consensus over individual differences in subjective assessments of EVA events. For the same reasons, quantitative analyses of skill can enhance the influence that EVA debriefs and "lessons learned" have on training. Relatedly, development of EVA simulators can be expedited by quantitative analyses insofar as they provide descriptions of essential EVA events that are commensurate with engineering descriptions and technology specifications.

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13. ABSTRACT (Maximum 200 words) This report describes the theoretical and operational foundations for our analysis of skill in extravehicular mass handling. A review of our research on postural control, human-environment interactions, and exploratory behavior in skill acquisition is used to motivate our analysis. This scientific material is presented within the context of operationally valid issues concerning extra-vehicular mass handling. We describe the development of meaningful empirical measures that are relevant to a special class of nested control systems: manual interactions between an individual and the substantial environment. These measures are incorporated into a unique empirical protocol implemented on NASA's principal mass handling simulator, the precision air-bearing floor, in order to evaluate skill in extravehicular mass handling. We discuss the components of such skill with reference to the relationship between postural configuration and controllability of an orbital replacement unit, the relationship between orbital replacement unit control and postural stability, the relationship between antecedent and consequent movements of an orbital replacement unit, and the relationship between antecedent and consequent postural movements. Finally, we describe our expectations regarding the operational relevance of the empirical results as it pertains to extravehicular activity tools, training, monitoring, and planning.				
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