UNDERSTANDING SKILL IN EVA MASS HANDLING:

IV. AN INTEGRATED METHODOLOGY FOR EVALUATING SPACE SUIT MOBILITY AND STABILITY

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VOLUME 4

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Acronyms

DOF	Degrees of Freedom
EVA	Extravehicular Activity
EMU	Extravehicular Activity Mobility Unit
HEDS	Human Exploration and Development of Space
JSC	NASA Johnson Space Center
MIT	Massachusetts Institute of Technology
LMRC	Liberty Mutual Research Center
NASA	National Aeronautics and Space Administration
PLSS	Portable Life Support System
SMART	Suit Mobility Assessment in Real Time

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 human 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 an 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

The empirical investigation of EVA Mass Handling conducted on NASA's Precision Air Bearing Floor (PABF) led to a Phase I SBIR grant from NASA JSC. The purpose of the SBIR grant was to design an innovative system for evaluating space-suit mobility and stability in conditions that simulate EVA on the surface of the Moon of Mars. The approach we used to satisfy the Phase I objectives was based on a structured methodology for the development of human-systems technology. Accordingly the project was broken down into a number of tasks and subtasks. In sequence, the major tasks were (1) identify missions & tasks that will involve extravehicular activity (EVA) and thus the requirements for mobility of the EVA system both in the near and long term; (2) assess possible methods for evaluating mobility of space suits during field-based EVA tests; (3) identify requirements for behavioral evaluation by interacting with NASA stakeholders; (4) identify necessary and sufficient technology for implementation of a mobility evaluation system; and (5) prioritization and selection of technology solutions. The work conducted in these tasks is described in this final volume of the series on EVA Mass Handling. While prior volumes in the series focus on novel data-analytic techniques, this volume addresses technology that is necessary for minimally intrusive data collection and near-real-time data analysis and display.

1. Task 1 - Needs Identification

NASA’s program for the Human Exploration and Development of Space (HEDS) provides a fundamental set of goals for the next century. Whether the strategy beyond the space station involves the Moon, Mars, or both, it is certain that extravehicular activity will play an integral role in making that future a success. It is beneficial to understand the basis for EVA requirements in the context of the overall mission.

A mission to Mars, like the Apollo program, will involve extravehicular activity in a reduced gravity (3/8 Earth) environment. Unlike the Moon, however, EVA’s will take place within the Mars atmosphere. Providing crewmembers the capability to conduct tasks outside of a pressurized environment will be a central focus of a potential Mars mission design.

The human exploration of Mars will be a tremendous undertaking, and surface operations will be the most important portion of the mission. The nominal duration on the surface will be 500-600 days, compared to 21 hours for the first Apollo mission. Mission preparation will assume a minimum number of EVA’s; however, flexibility will be built into the planning so that each astronaut will have the freedom to use EVA to adapt to changing needs. Extravehicular tasks during a Mars mission would include:

- surface system checking and verification
- maintenance of habitat and scientific facilities
- conducting scientific experiments, including geology field work, sample collection, and operation of instruments
- contingency EVA in-transit between the Earth and Mars

1.1 Characteristics of EVA Environments and Tasks in Future Missions

Humans required to work on the surface of Mars, on the Moon, or outside the spacecraft during orbital flight, are confronted with a hostile environment incompatible with human life support needs. These hostile environments necessitate the use of suits which protect against temperature variations, absence of ambient air pressure, and the absence of a breathable atmosphere. The suits that result from these demands are often bulky and restrictive to natural human movement. This is a problem because the reason for having a human presence on a planet surface is to perform work. In other words, life support is a means to an end: allowing astronauts to work in space. It follows that *work suppor*t is as important a means to this end as is life support. The “Mars Reference Mission” report calls for the development of EVA Systems which entail a lightweight, reserviceable, and maintainable suit and portable life support system (PLSS), and durable, lightweight, high mobility suits and gloves.

The report goes on to state “The EVA system will have the critical functional elements of a pressure shell, atmospheric and thermal control, communications, monitoring and display, and nourishment and hygiene. Balancing the desire for high mobility and dexterity against accumulated risk to the explorer will be a major design requirement on a Mars EVA system.”

The work depicted in the Mars Reference Mission will occur in a reduced gravity environment with an average atmospheric pressure at the “zero datum” of less than 1% that of Earth. The atmosphere is 95% carbon dioxide, containing only traces of oxygen,. Being the fourth planet in the Solar System, it orbits the Sun at a mean distance of 227.7 million kilometers. The average temperature on the Martian surface is of about -48°C, with extremes below -100°C at the poles. Moreover, because of the absence of the moderating effect of the oceans, the surface is very responsive to temperature gradients. Measurements from the Pathfinder lander revealed that if a person were standing on Mars, the temperature difference between his feet and his chest would be of approximately 15°. Diurnal temperature variations of 70° were measured as well as peak temperature gradients of 20° per minute in the morning.

1.1.1 Bipedal locomotion for significant distances Extravehicular activity in the weightlessness of low Earth orbit has been successfully performed numerous times. Experience in reduced gravity environments such as the moon or Mars, however, is far from mature. In order to reach work sites of interest Lunar or Martian explorers will be required to locomote over significant distances across a terrain of varying topology and surface types (rocky, sandy, etc). Advanced space suits must be designed to facilitate walking and accommodate for new tasks, which rely on balance. The limited experience from lunar EVA was enough to mandate serious efforts to enhance mobility and flexibility. In point of fact, several Apollo astronauts cited these issues as the most important factors in increasing productivity.

In addition to the limited experience in the partial gravity (1/6 g) of the moon, some studies of human performance have been conducted in reduced gravity environments. Data have been collected, for example, during parabolic flight on the KC-135 (Newman, Alexander & Webbon, 1994). Generally, the results suggest that oxygen consumption for a given exercise is reduced in partial gravity. Results also suggest that the mechanics of locomotion would be modified on the surface of the moon or Mars.

Data from parabolic flight and water immersion show significant reductions in peak force during locomotion over a range of velocities in partial gravity. A reduction in stride frequency occurs. Change in the stride frequency has no noticeable effect on the amount of time that the supporting leg is in contact with the ground. Locomotion in reduced gravity environments has been shown to require less muscular force. Because stepping frequencies are higher in higher gravity levels, coupled with the fact that the time of contact with the ground is the same across these different levels, an overall reduction in metabolic resources is anticipated. These characteristics are coupled with an increased aerial time (several tenths of a second) that results in a trend towards loping (one footed hopping) as the gravity drops less than that of Earth.

1.1.2 Activities at the worksite The Mars Reference Mission report states “The ability for individual crew members to move around and conduct useful tasks outside the pressurized habitats will be a necessary capability for the Reference Mission. EVA tasks will consist of constructing and maintaining the surface facilities, and conducting a scientific exploration program encompassing geologic field work, sample collection, and deployment, operation, and maintenance of instruments.”

Once at a worksite of interest humans will be required to perform a variety of tasks which will consist of generic activities that are very common on Earth. Such activities present special challenges during EVA. How to accommodate the demands of these activities within an EVA system is poorly understood. These generic activities include:

- the use of tools and equipment
- lifting and placing of masses of various size and weight
- reaching and touching for more subtle manual control
- hammering, prying, tool use
- carrying masses of various size and weight
- bipedal locomotion for repositioning relative to workspace
- ingress and egress of vehicles

An EVA system must permit mobility, while at the same time provide stability. The crewmember must have adequate sensory input including visual and haptic stimulation. This has implications for design of helmets as well as gloves and boots. Mobility, per se, can be influence by the amount of effort required simply to move against the resistance of the suit joints or fabric. Such factors, even it subtle, can have a significant impact on coordinated movement during skilled tool use and interaction with a cluttered environment.

1.2 Designing an EVA System

As with orbital EVA, it will be necessary for crewmembers to wear protective suits in order to provide life support during a Martian or lunar surface EVA. The suits worn must be able to provide appropriate levels of mobility and comfort so that crew are able to move and work over a period of several hours. These mobility requirements are qualitatively different to those in weightlessness. One significant concern focuses on providing the extravehicular crewmember with suitable mobility features in a pressurized suit without sacrificing appropriate levels of comfort or work capability.

NASA personnel have indicated that “Future work must be conducted to determine how much mobility is adequate for a planetary surface mission, which mobility systems are the most critical to provide that capability, and if those requirements can best be met through a soft or hard joint design. NASA is continuing to characterize representative geological exploration tasks and the contributions to total suit mobility each space suit joint system offers, as well as to explore contemporary suit joint designs so that when people set foot on some distant planetary surface, they will have the most appropriate suit to wear.” (Kosmo & Ross, 1998).

Throughout the history of the Space Shuttle program, the extravehicular mobility unit has been an excellent asset to the space program. It is important to keep in mind, however, that the EMU was designed for weightless orbital operations that utilize the upper body for mobility. As a result, its design will not fare well in the coming surface activities on the moon or Mars. For example, the suited subject could not touch his knees to the ground during the evaluation tests. Evaluating the EMU “out of its element” does highlight several of the important features needed to successfully design a suit for planetary exploration. Specifically, lower torso mobility would need improvement, which could be accomplished through the enhancement of hip mobility, ankle rotation, and waist flexion. One positive feature of the current EMU was the waist bearing, which allowed rotation for specific tasks.

The limited mobility of the Apollo suit (A7LB) would require additional waist and scye bearings, as the soft joint systems did not allow adequate range of motion in the waist, hip, and upper arm. The lunar EVAs of the Apollo program were a success, but limited mobility was offered by the A7LB. A systems engineering approach was used to design the Apollo EVAs, which accounts for the program success. Complemented by mobility aids, tools, and rovers, and well planned mission operations, the Apollo system enabled the success of lunar exploration. Future endeavors, either on the Moon or Mars, must continue to apply this multifaceted design approach. Consequently new suit designs are under consideration for these future human visits to Mars.

The amount of mobility and stability required for future planetary missions must be further investigated. By doing so, research and development of new suit designs will be augmented by better-defined requirements. These requirements, in turn, will help engineers address the fundamental questions that must be answered. One such question pertains to the choice of a hard suit (like the shuttle EMU) or a soft suit (like the Apollo).

1.3 Current Evaluation Methods

A fundamental requirement human work on the Moon or Mars is a space suit that is designed, tested and evaluated with respect to mobility of posture and movement. Given the success of prior EVA programs, suit research and development can be done with one eye on the past and the other toward the future. There are a variety of approaches to develop EVA systems, ranging from ground-based tests to flight tests. The current EVA technology program (see: http://www.jsc.nasa.gov/xa) utilizes such approaches for enhancements to the EMU and development of suits for Lunar or Martian exploration.

Prevailing practice for assessment of astronaut tasks and space suited performance involves measurements in restricted and artificial experimental settings (most often with the motions of single isolated joints), or largely qualitative and subjective observations in more representative experimental protocols (e.g., neutral buoyancy, air bearing floor, or suspension). Critical data for the further development and refinement of advanced space suits necessitates accurate measurements of whole-body mobility with and without the use of a pressure suit while performing representative astronaut tasks in high-fidelity test scenarios.

1.3.1 Quantitative measurement of suited mobility While NASA has successfully employed videometric analysis of joint mobility in laboratory conditions, these techniques are not well-suited for operation in the field. Limitations to the successful use of videometric technology include (a) dependence on line of sight for successful acquisition of motion, (b) the need for controlled lighting conditions (in the field, backgrounds can change from bright sky to dark terrain, cloud movement can cover and reveal the sun), (c) limited extent over which accurate measurements can be made, (d) the necessity for multiple cameras when several points need to be tracked, (e) and complex motions including rotations away from a single camera's line of sight. While many videometric motion tracking systems possess automatic tracking capabilities, these capabilities often fail to perform adequately under such challenging conditions. The alternative is manual tracking which is labor intensive and time consuming (see Section 2 for more information on motion tracking systems).

1.3.2 Qualitative measurement of suited mobility. The "objective" measurements of suit mobility and performance are often supplemented with "qualitative" measurements gathered using verbal feedback and the compilation of lessons learned. These data are extremely valuable resources, but the methodology requires careful use. It is a fact that people sometimes prefer technology features or designs that do not necessarily provide them with the best performance. This lack of association between preference and performance occurs because the features which influence preference may not be the same features that influence performance (Anthony & Wickens, 1995). Ultimately the value of the qualitative data is enhanced with reliable, quantitative measurements of performance.

1.3 Needs Summary

Clearly, there is a need for an objective, reliable methodology for evaluating suit mobility and stability in high fidelity simulations of anticipated future extravehicular environments. On the basis of their experience, suit engineers at Johnson Space Center have identified measurement of joint range of motion as a critical index of suit performance. However, these engineers have had limited success in acquiring such data under high fidelity field trials in the KC-135 (Test Report: CTSD-ADV-321), or in desert locations such as in Cinder Lake and Grand Falls, Arizona (Test Report: CTSD-ADV-338), and Silver Lake (Mojave Desert), California (Test Report: CTSD-ADV-360).

In the "Space Suit Comparative Technology Evaluation Test Plan" (Test Report: CTSD-ADV-344), the objectives are described as follows, "Collect both subjective and objective data regarding mobility systems performance characteristics between various advanced soft suit and hybrid space suit assemblies. Down-select the preferred mobility technologies and overall torso structural features..." The report proceeds to call for mobility evaluation during:

- mockup science module deployment
- hammering task
- cross body reach
- walking dynamics on level & inclined surfaces
- stepping over obstacles
- retrieval of objects
- zero-gravity performance
- strength evaluation tasks

A system is required to acquire joint motion data during suited movements accurately and reliably in the field. Moreover, this system must be sufficiently adaptable to accommodate: different suit designs with different joint configurations; measurement of shirt-sleeved performance; a wide variety of tasks and test scenarios including the KC-135 and the desert.

2. Task 2 - Assess Methods for Evaluating Mobility and Stability

The core of a system compatible with the needs described above will entail a method of measuring human joint motion. Since this is such a crucial component of the system, Task 2 is devoted to evaluating such technology. The intent of activities described in **Task 2 (Section 2)** was to perform a survey of the wide range of methods for evaluating mobility and stability. This activity occurred prior to the definition of system requirements described in **Task 3 (Section 3)**, so that the system requirements could be utilized to perform a “triage” on methods for evaluating mobility and stability. This triage was designed to enable detailed evaluation of a specific “class” of mobility evaluation technology compatible with the system requirements **(See Task 4, Section 4.1)**.

Human joint motion measurement systems exploit a number of different technologies and modes of operation. One class of systems can be characterized as those which employ sensors and sources that both are on the body (e.g. a glove with piezo-resistive flex sensors). The sensors generally have small form-factors and are therefore especially suitable for tracking small body parts. While these systems allow for capture of any body movement and allow for an unlimited workspace, they have been considered obtrusive and generally do not provide 3D information relative to a fixed external reference frame. A second class of systems employ sensors on the body that sense artificial external sources (e.g. a coil moving in a externally generated electromagnetic field), or natural external sources (e.g. a mechanical head tracker using a wall or ceiling as a reference or an accelerometer moving in the earth’s gravitational field). Although these systems provide 3D information relative to a fixed external reference frame, their workspace and accuracy is generally limited due to use of the external source and their form factor restricts use to medium and larger sized body parts. A third class of systems employ an external sensor that senses artificial sources or markers on the body, e.g. an electro-optical system that tracks reflective markers, or natural sources on the body (e.g. a videocamera based system that tracks the pupil and cornea). These systems generally suffer from occlusion (no line of sight), and a limited workspace, but they are considered the least obtrusive. Due to the occlusion it is hard or impossible to track small body parts unless the workspace is severely restricted. The optical or image based systems require sophisticated hardware and software and are therefore expensive.

Strengths and weaknesses are listed below for various classes of motion tracking systems. The organization of systems into these classes based on the sensing medium (e.g., acoustic, optical, electromagnetic, mechanical) is consistent that used by others (Ferrin 1991, Meyer et al 1992 and many others) and with the classification described above.

2.1 Goniometric

Goniometric technologies include potentiometers, piezoresistive material, strain gauges, and fiber optic materials:

- Many of these technologies do not allow for registration of joint-axial rotation (e.g. pronation/supination of the wrist).
- All the technologies use body-centered (joint-angle) coordinates.
- There is no external source or reference necessary, i.e. the workspace is in principle unlimited.
- Due to the fact that these systems are worn on the body they are generally considered obtrusive.
- Resolution, static/dynamic range, bandwidth and latency are all limited by the interface circuitry, generally not by the sensors.
- Most of the technologies have small form-factors and are therefore especially suitable for

small body parts (finger, toe). For larger body parts the accuracy of these technologies may be reduced due to body fat.
- Bending or flexing sensors across joints involves a transfer of joint angle to the bend angle of the strip which may reduce the accuracy of the technology, although the sensor itself may have a high repeatability. Each individual sensor must be calibrated for each individual user.

2.2 Mechanical/Magnetic

- The external source does provide in most cases 3D, world-based information, i.e. joint-axial rotations can be measured.
- The form-factor is in most cases fairly large so that the technologies usually apply to larger body parts (i.e. not for finger or toe), imply some obtrusiveness and may have limited accuracy due to inertia of the sensor/receptor (the receiver may shift due to skin/muscle movements). Additionally, there will be some offset introduced due to the receiver size.
- Most of the technologies involve some computing which may increase response latency.
- Resolution, static/dynamic range, bandwidth are all limited by the interface circuitry, generally not by the sensors.
- The technologies that use an artificial external source have a limited workspace.

2.2.1 Mechanical. Available technologies include potentiometer / optical encoder, externally attached via mechanical linkage (Shooting Star Technology head tracker, Fake Space BOOM, Immersion Probe, Sutherland headtracker, various mice). These systems can be described as high accuracy, high repeatability, low latency (no filtering), bulky, obtrusive/encumbering, small workspace, best useful for free-space movements, compensation necessary for inertia of system

2.2.2 Magnetic. Systems differ on the characteristics of the magnetic field generator:

DC EM pulse (Ascension Technology 6DOF tracker)
high accuracy, medium repeatability (interference from the earth's magnetic field and, less, ferromagnetic materials), medium dynamic accuracy (filtering), computing intensive, small workspace, medium latency
AC EM field strength (Polhemus 6DOF tracker)
high accuracy, medium repeatability (interference from ferro-magnetic materials), computing intensive, small workspace, medium latency
AC EM field, phase coherent
high accuracy, medium repeatability (interference from metallic materials), multiple separately located transmitters/receivers

2.3 Optical

- These tracking technologies are generally the least obtrusive of movement tracking technologies.
- Videocamera-based technologies are limited by occlusion. For movements of larger body parts this may be solvable, but for e.g. fingers, two closely interacting hands, or two closely interacting persons it remains a major problem.
- Videocamera-based technologies are computing intensive due to difficulties with staying locked onto the body part or marker and/or the involved transformations of data, so that response latency may be high.
- The performance of videocamera-based technologies is dependent on the type of lens or the field of view of the camera. Videocamera-based technologies are operational in a limited workspace only due to the field of view of the camera(s). If the field of view of one camera is

increased, resolution is decreased.
- Varying or unusual illumination of the environment may interfere with proper operation of the system.
- Conventional 30 or 60 frames per second technology provides insufficient bandwidth, i.e. special high-speed cameras are required.
- The amount of instrumentation generally remains the same independent of the number of points tracked.
- *Passive* or *active* markers have to be attached to the body part which introduces an offset. Special care has to taken to select and position a marker.
- Active systems utilize active markers or beacons which are less susceptible to conditions to illumination, but they require a power source and associated cable attached to the markers.

A new class of *noninvasive* tracking technology is currently under investigation at the University of Pennsylvania (Dr. Norman Badler: http://www.cis.upenn.edu/~hms), at the Japanese National Institute of Bioscience and Human-Technology (Dr. Masaaki Mochimaru: http://www.aist.go.jp/NIBH/ourpages/mochi/markerless-e.html), and at Liberty Mutual Research Center (Hsiang et al., 1998). These systems are intended to utilized computing power and specially developed algorithms built to reduce the complexity of human motion by understanding biomechanical constraints on motion. The intent is develop a system which can take a single camera view of a human moving naturally, in which no special lighting, body attachments, or external calibration is utilized, and one can extract accurate and reliable movement kinematics. Each of these groups are utilizing different approaches to solve essentially the same problem. Currently the most mature of the three is that from Liberty Mutual Research Center.

3. Task 3 - Identify Requirements for Behavioral Evaluation

On the basis of the material reviewed in Section 1, and by soliciting input from the suit evaluation team at NASA Johnson Space Center, a set of design requirements were assembled for an acceptable system for field evaluation of suit mobility and stability. The following list summarizes the requirements and organizes them into logical clusters. The first cluster plays an key role in Task 4 (see Section 4.1).

- will operate to acquire suit mobility data independent of line of site
- allows the test subject unrestricted movement: untethered and operable within a 600m diameter test site
- provides capability for verification of accurate angular range of motion measurement
- provides online, near real time data to verify system and data integrity
- can perform these measurements in the field (desert, KC135, etc)
- has a maximum sample rate of 100 Hz per channel

- is operable (end to end) by Crew & Thermal Systems Division employees with minimal training
- provides online, near real time data to evaluate joint range of motion
- provides capability for remote operation
- provides capability for intermittent data collection during task performance (e.g, capability to activate the system to collect data at specific intervals during a 45-minute test).

- initially to measure suit-joint range of motion, with later adaptation for human joint ROM
- provides data in the form of suit joint angular motion time series
- has a measurement resolution of <1.0 deg
- can monitor 16 channels simultaneously (equivalent to 16 suit joint axes of motion)

- provide archive media for data storage

- package (transducers, power supply, amplifier, data storage/buffer, telemetry transmitter) attached to the suit “to be as light as reasonable possible”
- can operate from battery for 4 hours continuously
- compatible with current onboard PLSS power sources
- is portable (total mass: c. 20Kg , stowed dimensions: suitcase size)
- can be destowed, and implemented ready for data collection in c. 30 minutes (destow, set up work station, attach sensors, verify operation, etc).

- can operate in temperature range of 0-40deg Celsius.
- can operate at an ambient pressure range equivalent to 0-7000 feet altitude
- can tolerate dust contamination to permit outdoor desert operation
- utilize ruggedized laptop for data processing/display (operable 120/240v or battery)

4. Task 4 - Identify Necessary and Sufficient Technology

In using the requirements from **Task 3** to identify candidate technologies for an innovative mobility measurement system, we found that the technologies fell into three categories:

1) The **joint-motion transducer** should permit the accurate and reliable measurement of suit joint range of motion. The **suit-transducer interface** provides a nonintrusive, lightweight, simple and reliable method for attaching the joint motion capture transducers to the suit and suit joints.

2) The **data acquisition system** acts to gather, process, display and store data from the joint motion capture transducers in a manner compatible with the requirements above.

3) The **data verification, monitoring of activities & worksite** element should act to gather, process, display and store data about the position and orientation of the test subject in relation to tools, equipment and other features at the worksite. In addition, this element should allow verification of satisfactory operation of the Join Motion Capture Transducers.

The candidate systems evaluated in this task are subsequently prioritized in **Task 5** (Section 5). A work plan for developing the three components of the innovative mobility measurement system is described in Section 5.

4.1 Joint Motion Transducer

A comprehensive technology review was previously performed in **Task 2** because the core component was determined to be a method of satisfactorily measuring human joint motion. On the basis of this information and on the basis of the system requirements described in **Task 3 (Section 3)**, a “triage” on methods for measuring human joint motion can be performed. Final prioritization of technologies occurs in **Task 5.**

Table 1. Comparison of several alternative motion capture technologies

	Independent of line of site	**Operable over large test site**	**Untethered operation**	**Provides external reference & worksite monitoring**	**Operable in natural lighting conditions**	**Sample rate**

Optical: Passive	No	No	Yes	Yes	Yes/No	60-1000Hz+
Optical: Active	No	No	Yes/No	Yes/No	No	200Hz
Optical: Noninvasive	No	Yes	Yes	Yes	Yes	30/60Hz
Mechanical	Yes	No	No	No	Yes	?
Magnetic	Yes	No	No	Yes/No	Yes	c. 100Hz
Ultrasonic	Yes	No	?	No	Yes	?
Goniometer	Yes	Yes	Yes	No	Yes	>100Hz

Table 1 compares several alternative motion capture technologies with respect to the system requirements that best differentiate among them (see Section 3, first cluster of requirements). While no single technology satisfies all the requirements, the goniometric technology is the most compatible, being able to operate independent of the line of sight, not restricted to a small test site volume, independent of lighting conditions, and able to provide joint angular motion data at a satisfactory sample rate. The only requirement not met is the provision of external worksite monitoring.

Having made a choice to pursue goniometric technology for the measurement of joint motion and mobility, candidate technologies will be reviewed in further detail below. There are several candidate goniometric technology solutions including Measurand's Fiber Optic SHAPE SENSORS™, Biometrics' strain gauge sensors, and Virtual Technologies Inc. piezoresistive sensors. These technologies are described in the following subsections.

4.1.1 Measurand

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Fredericton, New Brunswick
Canada, E3B 6Z9

Phone: 506-462-9119
Fax: 506-462-9095
Email: sales@measurand.com

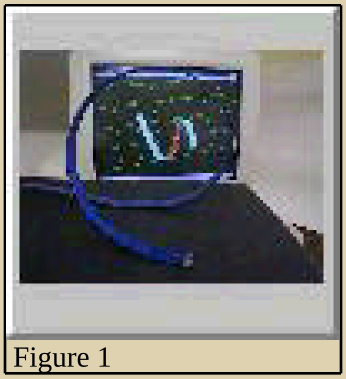

Figure 1

Measurand's patented SHAPE SENSORS™ and SHAPE TAPE™ translate curvature (shape) into an electrical signal through the use of light. The S1280C SHAPE TAPE™ (Figure 1) is a general purpose six degree of freedom (6DOF) distributed measurement system: "the tape that knows where it is." It includes a fiber optic shape sensor array in tape form connected to an interface box. Signals from the interface box are read by an A/D card operating in a Windows 95 environment in a PC. The A/D also sends control signals to the interface box. Included software allows viewing a real time image of the SHAPE TAPE™ on the computer. An S1280C system includes the SHAPE TAPE™, interface box, wall mount power supply, A/D board, and imaging software. S1280C SHAPE TAPE™ can be supplied with different sensor spacings and locations. Length and width may also be varied. (SHAPE TAPE™ is produced under license from the Canadian Space Agency.)

Interface box (IB) dimensions: 3.5 x 9 x 17 cm nominal
Wall mount power supply input: 120 VAC 60 Hz, 5W nominal
Cable from IB to A/D card: 8mm x 2 m nominal, 37 pin connector at card
Curvature range: ±40 mm radius bend, ±3.8 deg/cm twist
Curvature resolution: 0.01% of range
Positional range in draped form: ±300 mm
Positional resolution in draped form: <±1.5 mm (1 sigma) nominal
Operating temperature: -20 C to + 50 C
A/D resolution: 12 bit
Update rate: 30 Hz nominal
System requirements: Windows 95, >100 MHz, 16 meg ram, 256K cache

S220 New Peel and Stick SHAPE SENSOR™ have no built in cantilever; instead, they are designed to be attached to a remote object that bends. With care (see instructions) this may be done repeatedly. To work with many substrates, including those with an initial curvature, the FS range is greater than for an S210 sensor. An S220 sensor may be mounted on a spring steel cantilever and used like an S210 SHAPE SENSOR™ (Figure 2). Resulting performance may be estimated from the S210 data sheet, with sensitivity reduced to approximately 1/3 of the S210 values.

Figure 2

Full scale (FS) range: ±1.5V for ±4 cm radius (0.25 rad/cm).
Output voltage for straight sensor: 2.5 V, ±0.2V.
Linearity and hysteresis combined, on 0.127 x 6.35 mm steel cantilever: ±1% of FS.
Small scale hysteresis and repeatability, on 0.127 x 6.35 mm steel cantilever:
3000 m radius (3.3 µrad/cm) = ±0.001% of FS, 1 Hz bandwidth.
Noise floor: 0.07 mV rms/Hz-1/2. 3dB Bandwidth: 1.6 kHz.
Temperature sensitivity, offset: ±2% of FS, -40 C to +70 C.
Environmental: -40 C to +70 C, hermetically sealed.
Stiffness of 15 mm section mounted as cantilever (no metal): 1.9 gf/mm (similar to overhead projector transparency stock).
Excitation: 5 to 15 VDC (Supply current at 5 VDC, 15 C: 5mA)
Electrical Connections: Male 3 pin AMP connector - Pin 1: Common, Pin 2: Power, Pin 3: Signal

S720 Miniature Dynamic Joint Angle SHAPE SENSOR™ (Figure 3) is a comfortable, flexible, bipolar joint angle sensor. Can be used to measure the angle of any small 1 degree of freedom joint including fingers and toes. Because of its small size, the S720 can be mounted with re-usable, flexible adhesive polymer (supplied), which allows easy adjustment to a natural form along the neutral axis of the joint. It may be used either directly on the skin, on a glove or on biocompatible tape.

Full scale (FS) range: ±1.0V for ±90 joint angles
Output voltage for straight sensor: 2.5 V, ± 0.2V.
Linearity and hysteresis combined: ±1.5% of FS.
Noise floor: 0.07 mVrms/Hz-1/2.
3dB Bandwidth: 1.6 kHz.
Temperature sensitivity, offset: ±2% of FS, -40 C to +70 C.
Environmental: -40 C to +70 C, hermetically sealed.
Excitation: 5 to 15 VDC (Supply current at 5 VDC, 15 C: 5mA)
Electrical Connections: Male 3 pin AMP connector - Pin 1:

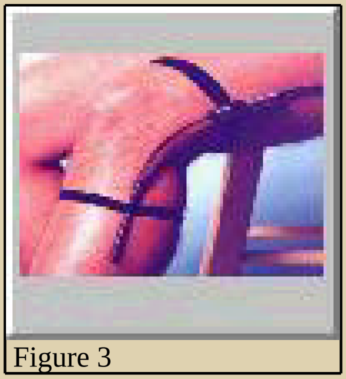

Figure 3

Common, Pin 2: Power, Pin 3: Signal

4.1.2 Biometrics Ltd.

Biometrics Ltd
Unit 25 Nine Mile Point Industrial Estate,
Cwmfelinfach,
Gwent,
NP1 7HZ
UK
tel +(44) 1495 200 800
fax +(44) 1495 200 806
North American toll free tel 800 543 6698
E Mail 100413.722@compuserve.com

Biometrics' goniometers and torsiometers are ideal for quick, simple and accurate assessment and analysis of joint movement in one or two degrees of freedom. The sensor is attached over the joint using double sided medical tape. The telescopic endblock compensates for changes in distance between the two mounting points as the limb moves. This enables the units to be worn comfortably undetected under clothing without hindering the actual movement of the joint. A comprehensive range of instruments is available from a simple hand held static display, to a pocket sized multi channel Data Logger enabling accurate ambulatory monitoring.

4.1.3 Virtual Technologies Inc.

Virtual Technologies, Inc.
2175 Park Boulevard
Palo Alto, California 94306
Tel. (650) 321-4900
Fax. (650) 321-4912
Email info@virtex.com

The CyberGlove features Virtual Technologies' patented resistive bend-sensing technology that is linear and robust. The sensors are extremely thin and flexible and produce almost undetectable resistance to bending. Since the sensors exhibit low sensitivity to their positioning over finger joints and to the joints' radii of curvature, each CyberGlove provides high quality measurements for a wide range of hand sizes, and ensures repeatability between uses. Calibrations typically need not be updated, even after months of use.

CyberGlove™ Specifications

- Sensor Linearity: 0.62% maximum nonlinearity over full range of hand motion.
- Sensor Resolution: 0.5 degrees; remains constant over the entire range of joint motion.
- Repeatability Between Glove Uses: Standard deviation of typically 1 degree.
- Off-Axis Bending: Sensors respond primarily to bend about the single desired sensor axis.
- Interface: RS-232 with selectable baud rates up to 115.2 kbaud. Analog output also provided.
- Update Rate: Up to 112 records/sec when filtered (18 sensor records). Up to 149 records/sec
- when unfiltered. Preset sample period or polled I/O. (Higher rates possible when fewer sensors are enabled).

Physical Characteristics

Item	Dimensions	Weight
CyberGlove	One size fits most	3.0 oz
Instrumentation Unit	10.00" x 6.25" x 2.75"	27.0 oz

Power Supply (USA)	4.36” x 3.10” x 2.28”	2.5 lb
Power Supply (Europe)	6.30” x 3.82” x 2.66”	3.5 lb

4.1.4 Suit/transducer interface. With the choice of a goniometric joint motion capture technology, it is crucial to provide an adequate and reliable interface method between the transducers and the suit. Specifically, the interface must allow for the transducers to be:

- easily and quickly attached
- easily and reliably secured
- resistant to slippage
- lightweight
- unrestrictive
- flexible enough to adapt to different suits & shirt sleeves

4.2 Data Acquisition System

To effectively utilize the measurement transducer and suit-transducer interface, the final component necessary is one which permits data acquisition over a large test site. Wired (tethered) data transmission is impractical both due to the size of the worksite (600m diameter) and the nature of the activities and worksite terrain. Onboard data storage is not acceptable as the primary data acquisition method in light of the requirement for near real time data presentation and evaluation. However, this method could be used for redundancy should primary DAQ method fail. The only method compatible with the requirements is a telemetry system. Two candidate systems have been identified.

4.2.1 KMT Telemetry DAQ

Kraus Messtechnik GmbH
Gewerbering 9, D-83624 Otterfing,
Germany
Voice +49-8024-48737,
Fax. +49-8024-5532 –
Home Page http://www.kmt-gmbh.com
E-mail: kmtgmbh@aol.com

A-DAT
Mr. Reinhold Badmann
29140 Buckingham Ave., Suite 2
USA - MI-48154 Livonia
FAX +1-734-458-1702
Phone +1-734-458-1701
E-mail: ADAT01@aol.com

4.2.2 KMT MC16/64 (Standalone computer and A/D system)

16 channels in the base unit, expandable to 32, 48, 64
Auto zero over the full measuring range
Sampling simultaneous
Total sample rate: 80, 40, 20, 10k Samples/s
Channel sample rate: total sample rate divided by 2, 4, 8 etc. (added sample rates of all channels is equal to the total sample rate),
Resolution: 12Bit, 72dB dynamic range
Software:µ-Lab and µ-Graph
Laptop: Panasonic CF-27 with 266Mhz Pentium Processor, 32MB RAM, 4 GByte HDD, 12.1‘‘ TFT-Color display (800x600) - Rugged design!
Interfaces: PCM (Miller) output with clock, transmitter output including excitation, single and multiple analog signal output (± 5V), 37 pin connector to IF16-Card (PCMCIA or Desktop) for data transmission
Power supply: 10-18V DC (optional 18-30V)

dimensions: 16 channel base unit: 320 x 260 x 130mm - 16 channel extension 320 x 260 x 60mm

Figure 4

4.2.3 KMT PCM 16 channel mini telemetry system

- 16 channels (2-4-8-16 channel mode)
- Analogue signal bandwidth 0 Hz-10 kHz/channel (2 CH mode)
- 80 kHz total scanning rate (2.45 GHz transmitter)
- 12 bit resolution
- Simultan scanning rate to all selected channel
- Anti-aliasing filters
- Distance up to 500m - more on request
- HF transmitter 2.45 GHz 20mW or (433.9 MHz 10mW)
- Dimensions encoder 150x85x80mm, decoder 160x85x80mm
- Power 10-32 V DC, 8 Watt

Figure 5

4.2.4 KMT D2/16 Mobile Mini DAT Recorder. The D-2/16 DAT Recorder (Fgiure 6) is a small and powerful data logger. The physical size and shock resistance is its major advantage against other data acquisition devices. This becomes apparent, whenever space or critical positioning is the issue. Well-tried examples are cars, trucks, trains, planes and heavy machines. The surveillance and analysis takes place online.

Over a serial PCM output, optionally also by RF telemetry, the data will transmit to a computer. Windows 95/NT based µ-LAB and µ-GRAPH Software can control the whole data transfer, hard disk storing, numerical and graphical online visualization, mathematical transformations, trigger monitoring and event-driven tasks. The latter feature

Figure 6

includes the possibility of signal level controlled data acquisition. This is especially useful for long term measurements, where continuous recording is impractical. Thus a periodic signal impulse can initiate a predetermined period of analog data acquisition.

The D-2/16 DAT can convert data from analog to digital and feed them direct to an PC without recording. Just as in recording mode the analog data are filtered and digitized and the DAT recorder works as an PCM encoder for serial or telemetry data transmission. An additional feature is the digital pulse channel for simultaneous recording of bit streams with clock rates from 0 to 20 kBit/s. This input is very suitable for PCM signals transmitted via telemetry from external encoders, input pulses from revolution or speed sensors and simple digital signals. With an optional encoder this bit stream can also used for recording 4 or 8 additional low frequency analog channels independent from the selected channel mode.

- Record and reproduce of 16 analog data channels, voice, date, time and digital signals
- Extremely small and rugged design for multiple application areas
- Usable in each position and therefore especially suitable for extreme mobile applications
- Very resistant against shock and vibrations
- Extremely adaptable to various measuring requests due to switchable number of channels and signal bandwidth
- Robust remote control box with bar graph display
- Computer interface for online data visualization, hard disk transfer and analysis
- Telemetry connection to computer interface for online data monitoring during mobile use
- Event-driven record commands by trigger signals or via remote control
- Automatic title number recording with fast search run in play mode
- Power supply DC 10 ... 32 V, optional battery and mains 220V AC

4.2.5 Wireless Data Corporation Telemetry DAQ system

Wireless Data Corporation
620 Clyde Avenue
Mountain View, CA 94043
Voice: 650-967-9100
http://www.wirelessdatacorp.com

The Model TR80 is a wireless data acquisition system for use in industrial applications. This seamless flexible system replaces clumsy and expensive wiring. Its use of frequency hopping makes it highly resistant to external interference and multi path fading and its RS-232 interface allows it to be integrated into most applications. Multiple nodes (up to 255) can be operated on a single channel.

- 8 or 16 Analog Channels
- 5000 samples per second aggregate throughput
- 12 bit A/D
- Simultaneous Sampled Inputs
- Frequency hopping spread spectrum wireless modem
- Buffered acquisition allows data to be samples at 100,000 s/s then transmitted, 8 megabyte on-board buffer
- Up to 250 kbps transmission data rate
- Supports up to 255 nodes on a single network channel
- License free 2.5 GHz operation (under FCC, part 15 and ETS Standards)
- Error free protocol
- Distance up to 1,000 ft. indoors, 3,500 ft. outdoors (line of sight). Greater distances with gain antennas (+2 miles).
- Dimensions 6.4” x 4.25” x 2”

- Power 5.5 to 10 VDC, 600 mA
- NEMA 4 enclosure
- LabView® Driver allows remotes to be controlled and data to be collected and displayed

The TR80 requires the user supply a laptop computer. It is also necessary to purchase LabView™ since the system software is based upon LabView.

4.3 Data verification, monitoring of activities & worksite

Since the goniometric motion capture system does not provide for any external worksite monitoring, it is necessary to consider a second, supplemental type of system for this purpose. The most compatible with the field conditions likely to be confronted in the desert is the optical-noninvasive type of system. Such a system is dependent simply on the presence of a video camcorder. Since the joint angle data will be gathered primarily with goniometers, this system is tasked with providing global worksite data and surveillance of crew-tool-environment interactions.

Section 2 reviewed optical measurement technology, which in addition to providing joint motion tracking capabilities, are able to provide global worksite data. The most suitable subset of the optical measurement technology is the “noninvasive” surveillance systems. These systems comprise a new class of video motion tracking technology, and exemplar systems are currently under investigation at the University of Pennsylvania (Dr. Norman Badler: http://www.cis.upenn.edu/~hms), at the Japanese National Institute of Bioscience and Human-Technology (Dr. Masaaki Mochimaru: http://www.aist.go.jp/NIBH/ourpages/mochi/markerless-e.html), and at Liberty Mutual Research Center (Hsiang et al., 1998). These systems are intended to utilized computing power and specially developed algorithms built to reduce the complexity of human motion by understanding biomechanical constraints on motion. The intent is develop a system which can take a single camera view of a human moving naturally, in which no special lighting, body attachments, or external calibration is utilized, and one can extract accurate and reliable movement kinematics. Each of these groups are utilizing different approaches to solve essentially the same problem. Currently the most mature of the three is the “Video-based Lifting Technique Coding” (VidLiTeC™) system from Liberty Mutual Research Center.

5. Task 5 - Prioritization and Selection of Technology Solutions

Activities in this task sought to identify the primary technology solutions compatible with three sources of requirements. The primary source are the system requirements identified in Task 3 (see Section 3). Additional guidance on the technology prioritization came from a desire to utilize where possible, state of the art, yet relatively “mature” COTS technologies. The third source of consideration was with regards to the potential commercial market for a system of this kind. A bundle of technology has been identified for integration into a system for Suit Mobility Assessment in Real Time (SMART). A preliminary design for the SMART system has been completed. This proprietary design is the basis for the Phase II SBIR proposal for development of the system.

6. Task 6 - Plan for Phase II

The Phase II SBIR proposal includes a two-year plan for development of the SMART system. The plan provides for extensive calibration and verification of the system both in the laboratory and in the field. Personnel and facilities at the NASA Johnson Space Center and at the Liberty Mutual Research Center would be utilized in the empirical evaluation of the system while under development.

7. Task 7 - Supplementary Research Issues

The primary objective of Phase I R/R&D was to produce a feasible plan for the development of technology that would fulfill the needs of NASA JSC for assessment of stability and mobility of advanced space suits in the field. The inclusion of a supplementary Task 7 in our Phase I work plan reflects the importance we see in the continuation of such cutting-edge research at NASA-JSC. In this section, we briefly consider questions about the evaluation of suit mobility and stability that have arisen during the course of this technology development effort. The intent of this consideration is to identify research issues that the EVA community may wish to pursue to further enhance suit development efforts

7.1 Methods for Evaluating Space Suit Mobility and Stability

A review of methods utilized in evaluating space suit mobility and stability allows categorization according to the dimensions shown in Figure 7. Figure 7 illustrates that evaluations can address isolated joints or components of the space suit, or the entire space suit; these evaluations can gather qualitative data and/or quantitative data; and these data may be used to describe pure kinematic features of suited performance, like range of motion, or to describe higher order performance factors such as how “usable” the suit is.

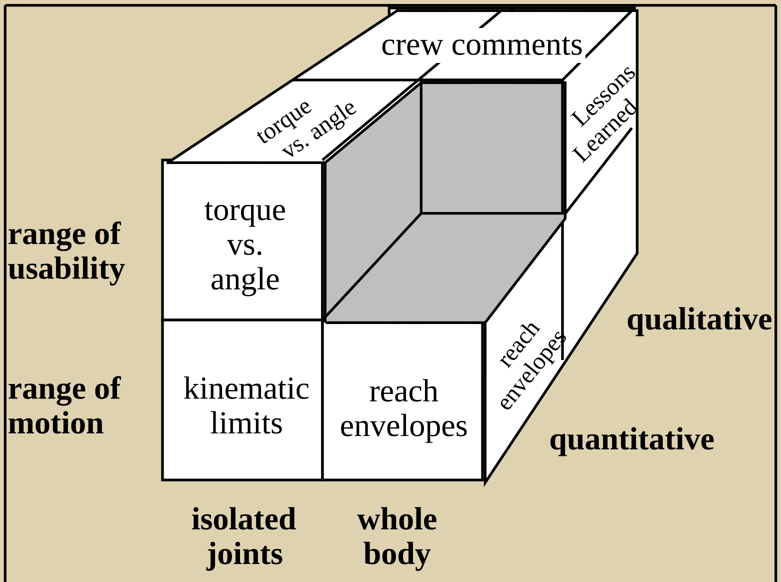

Figure 7. Classification of methods for evaluating space suit mobility and stability

On the basis of these dimensions, existing methods can be categorized. So, for example, a joint specific quantitative evaluation of range of motion would identify the kinematic limits about that joint (e.g. the elbow joint permits 125 degrees flexion/extension). A whole body (multi-joint) quantitative evaluation of range of motion allows for, among other things, the determination of the extent or reach envelopes (e.g Figure 8 illustrates reach envelopes for EMU operation while in the PFR). In conjunction with quantitative data gathered describing isolated and multijoint range of motion data, it is possible to gather qualitative data describing the same phenomena. In space suit evaluation, these data are most commonly acquired in the form of crew comments. These are very valuable, but complex, sources of information which have often been used to compile “lessons learned” documents. Typically these comments extend beyond the description of range of motion issues; crew are more likely to comment on what might be termed “range of usability.” Ultimately any multi-joint suit must be usable. The degree of usability can vary according to the posture or configuration of joints, and the location within a range of motion a joint is configured. Thus, for example in Figure 8, a reach envelope can be subdivided into “preferred work regions” reflecting a region in which the crew can perform work comfortable and reliably, and the nonpreferred regions, reflecting regions which may be reached, but may require such extreme postures that useful work can only be performed for very short times, or with high error rates.

This issue of “usability” is a complex one. Quantitative data describing the range of usability of single joints may be gathered as torque vs. joint angle data. Such data can reveal any nonlinearities in the joint, and any hysteresis. However, quantitatively evaluating the range of usability for complex, whole body motions is not simply an issue of additive concatenation of these single joint quantitative data. Our review of methods utilized in evaluating space suit mobility and stability revealed this category to be the one most inadequately represented. Hence, Figure 7 displays an open region with respect to this category.

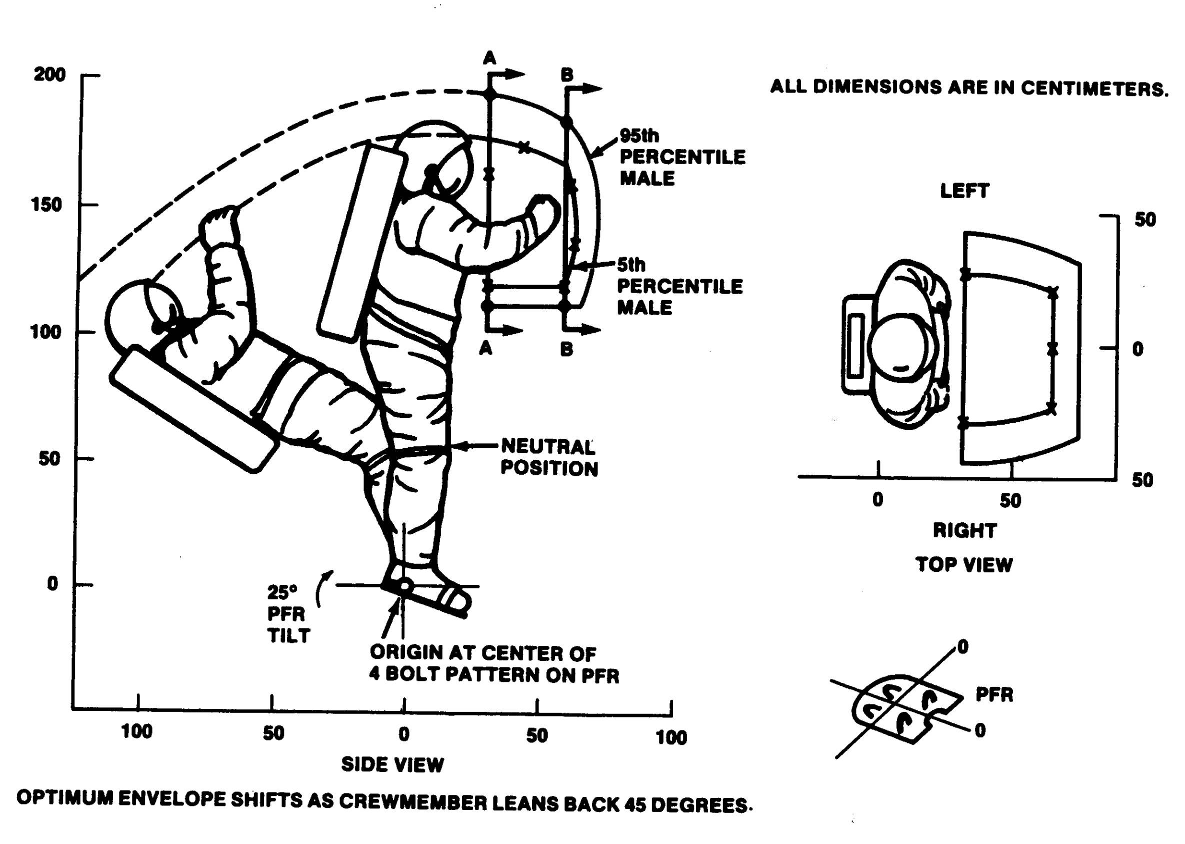

Figure 8. EMU reach envelopes while in the PFR

7.2 Evaluating Space Suit Mobility and Stability in whole body activities

Section 7.1 suggests attention needs to be turned to developing methods for the quantitative evaluation of the “range of usability” during suited, whole body, complex movements. These data should complement the qualitative data gathered from crewmembers concerning this feature.

Humans are exquisitely sensitive to the issues of mobility and stability, and will adapt their movement patterns, or work patterns according to what they know is stable, and how mobile they are. The most valuable information of this type is acquired during the performance of real tasks during actual missions, and during the performance of high fidelity simulations. However, it is unfeasible to perform all evaluations in the context of real missions or high fidelity simulations due to issues of expense, timeliness, availability, safety, etc. Therefore, how might this human sensitivity be quantified so as to allow an objective determination of suit usability in the most efficient and reliable fashion possible?

To accomplish this requires analysis of the whole process of suit performance evaluation methods. The high fidelity simulation (or actual mission) can be considered the center piece of the various methodologies (see Figure 9). However, there are several supporting methods which need to be exploited appropriately to ensure effective and efficient utilization of these high fidelity simulations. These methods include activities that can occur prior to human testing, including an evaluation of existing data on space suits and human performance, and analyses with computer models and simulations. On the basis of these methods, an efficient and robust test plan can be constructed for human-in-the-suit testing, ensuring high quality data using activities which have the most potential provide information on unknown aspects of suit performance.

During the course of these human-in-the-suit evaluations, efficiency and effectiveness could be increased by acquiring real-time or near real-time data, so that online verification of data quality and performance parameters is possible. This element is the focus of the SMART system developed in this Phase I project. However, the evaluation is not complete at this point. Post-test evaluations should continue, with a view to “closing the loop” so that the database of existing data on space suits and human performance is refined, allowing for the improvement of computer based mathematical models, and subsequently refining future field tests with humans in the suit.

7.3 Recommendations for future research

To implement the process described above, there are several areas which would benefit from further research and development.

7.3.1 Single and multijoint torque data

Prior to human-in-the-suit activities, comprehensive data on single joint charactersistics should be acquired in the form of torque vs joint angle data. These data will identify any hysteresis, and any nonlinearities across the range of motion. The presence of hysteresis and nonlinear behavior will act as significant constrains on human, multijoint performance. In addition to these single joint data, comprehensive data should be gathered on multijoint movements by simulating motions that are common in EVA tasks. These data will permit an evaluation of any interactions between joints, again the occurrence of any nonlinearities. None of these data require the presence of a human-in-the-loop.

NASA JSC owns the robotic space suit tester (RSST), an anthropomorphic robot designed and built by Sarcos Inc., and highly compatible with the acquisition of these single and multijoint data. The robotic tester is a human-sized robot that is inspired by biological principals incorporating joint actuators that can be thought of as agonist-antagonist muscle pairs. Body positions are recorded continuously throughout the simulated motion and highly accurate joint torques are measured, which previously could only be calculated theoretically via inverse dynamics calculations. The RSST’s right side is controllable, whereas the left side is only a mannequin.

In addition to the instrumented human-sized robot, highly accurate three dimensional *motion analysis* can be collected for movements. Finally for future work, a *master-slave control technology* is suggested whereby the robot wears a pressurized space suit and a human subject (i.e., astronaut) runs through choreographed simulated tasks. In this scenario, position of the space suit is recorded for all joints and required suit torque at the joints is calculated. This enhanced capability would allow for measurements of previously unattainable data, EMU joint torques during dynamic whole-body motions.

7.3.2 Quantitative evaluation of human-in-the-loop suit usability

During human-in-the-suit activities it is necessary to extend data gathering beyond quantification of human mobility into the acquisition of quantitative data compatible with the qualitative “user comments.” Such data reflect how the “whole” feels during the performance of realistic, high fidelity simulations and represent a combination of what traditionally might be referred to as mobility and stability. These data will permit the evaluation of nonuniformity of usability within a range of motion. It is recommended that efforts be made to develop procedures to acquire “near real-time” access to these data so as to permit online verification/adaptation of test plan and more efficient utilization of resources in the field.

A description of some candidate measurement indices compatible with skilled human performance in space suits is found in McDonald et al., (1997), Riccio et al., (1997), and Riccio & McDonald (1998).

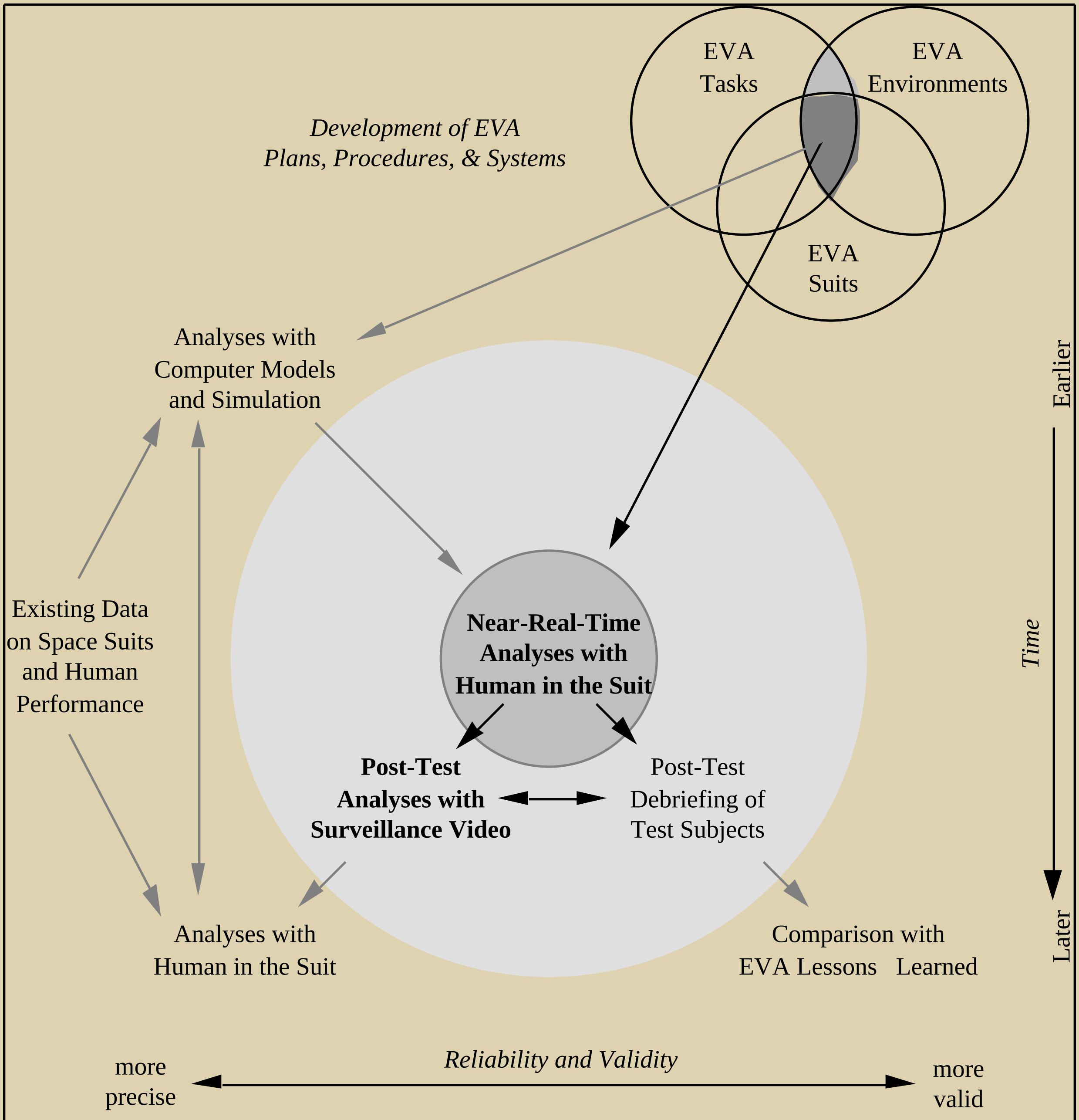

Figure 9. Schematic depicting the relationships among available suit performance evaluation techniques

7.3.2 Post test validation

The final area recommended for further research concerns the post test validation and utilization of the stability and mobility data gathered. Specifically, the human performance data need to be supplemented with data documenting the interaction of the human with their worksite tools, tasks and environment. The SMART system recommends the use of a system which will acquire such data with minimal operator overhead in a minimally invasive fashion, in a manner which is robust in field and requires minimal postprocessing.

However, there are issues regarding the optimal use of this technology in terms of how to effectively characterize the complex, multidimensional activities under observation. Further R&D aimed at optimizing this technology use will be necessary for comprehensive and efficient field based evaluation of suit mobility and stability.

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