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Remote Ergonomic Research in Space: Spacelab Findings and a Proposal

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This paper discusses ergonomics research using remotely situated video cameras in spacecraft. Two prototype studies of crewmembers working in the micro-G environments aboard the first two flights of Spacelab are described. Various aspects of crew restraint, stabilization, manipulation of controls, and mobilization were observed, operationally defined, and quantified by observing videotaped scenes of Spacelab crewmembers. In the first study, four performance behaviors were quantified to provide estimates of their frequency of occurrence and variation over the course of each of the flights. The behaviors and their mean percent of observed times were: Hand-Hold 32.2%, Foot Restraint 35.3%, Translation 9.4%, and Struggle 3.7%. Because we observed that nearly a third of a crewmember's time was spent inefficiently holding on with one hand while trying to work with the other, a second study was conducted exploring the use of foot restraints and hand stabilization. During 18 episodes of single-foot restraint, for example, there were 52 instances of hand stabilization and 135 instances of stabilization attempts with the other foot. The paper concludes with some defining characteristics of adequate foot restraints, and a proposal for extending this research model to future spacecraft studies.

THE SENIOR AUTHOR spent a sabbatical leave year as a human factors specialist with the Rockwell International team in the Space Station Freedom design competition. Designing work stations for the space station laboratory modules was difficult because of a lack of empirical information about the details of weightless performance. After an exhaustive literature search the work station designers were left with a few NASA reports of a general nature, some Skylab astronaut debriefing notes, and some information from our own interviews with astronauts. It seemed that we had no choice but to base our designs on this largely anecdotal information and our own imaginations. Then, just before returning to academe the senior author discovered some videotapes in Rockwell's archives which showed astronauts at work during flights of Spacelab. The Space Station design team members were eager to know if these tapes held information that might assist in our design task, so Rockwell officials asked the author to take the tapes to his laboratory and determine what information could be derived from them. This paper describes that effort, the shortcomings of its post hoc nature, and proposes a plan for remote research that will provide designers with needed human factors information about weightless performance.

Spacelab is a laboratory module which is carried into orbit in the cargo bay of the Shuttle orbiters (4). The Shuttle cargo bays are not pressurized so as the Shuttles ascend Spacelab is eventually exposed to the high order vacuum of low Earth orbit. Once in orbit the Spacelab and Shuttle experience near-zero gravity. The cargo bay doors are then opened exposing Spacelab and the Shuttle's radiators which are located on the inside panels of the doors. Spacelab is a cylindrical module about 7 m long and 4 m in diameter. The crew rides into orbit in the cabin of the orbiter and then enters Spacelab via a 1-m diameter tunnel that connects the orbiter's air lock with the Spacelab module. The temperature, air pressure, and humidity are essentially the same in the orbiter cabin and Spacelab. Together, they provide a shirtsleeve working environment for the crew. Crewmembers not on duty in Spacelab spend their time in the orbiter cabin.

Spacelab has flown a number of times: first aboard the orbiter Columbia for 10 d in 1983, and then aboard Challenger for 8 d in 1985. Spacelab flew again in May, 1991, in January, 1992, in November, 1993, and early in 1994. However, the studies conducted for this paper deal only with the first two flights. The primary tasks of the six-man crew on the first flight were to verify Spacelab's systems and to perform a series of experiments within the time constraints of the verification procedures. The seven-man crew on the second flight set up two teams and worked two 12-h shifts per day in Spacelab. Experiments on the two flights were conducted in materials processing, environmental observation, fluid mechanics, astronomy, and the life sciences.

The Spacelab module is only slightly smaller in diameter than the planned modules for the forthcoming Space Station, and about 0.5 m shorter. The internal configuration of Spacelab is similar to what is being planned for the Space Station, so Spacelab should provide a reasonably high fidelity simulation of what life will be like on board a space station laboratory module. While somewhat smaller than the Russian space station, Mir, the

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laboratory portions of the two modules are quite similar in configuration (2,1).

A considerable amount of anecdotal information was accumulated during the three times that the first U.S. Space Station, Skylab, was occupied in 1973–74 (3). However, there were two important differences between Skylab and Spacelab. Skylab was very much larger, and it had open metal grid floors. Skylab crewmembers wore special shoes that allowed them to secure themselves quickly, easily, and comfortably to the grid floor. Spacelab, however, has solid floors and cloth foot loops for restraint. Nevertheless, the Skylab data are valuable for comparison with those from Spacelab. For instance, in those places on Skylab where there were solid floor panels, cloth foot loops were provided, such as in front of the waste management unit. However, Compton and Benson point out that, "The foot restraints on the floor proved of little use" (3, p. 153). Jack Lousma was a crewmember on Skylab and also commanded a Shuttle flight. In an interview with the senior author, Mr. Lousma said that the Skylab crews were satisfied with the triangular grid foot restraints, and that, in his estimation, they were the best restraints yet devised. Nevertheless, both Mr. Lousma and Charles "Pete" Conrad, who commanded the first Skylab mission, told the senior author that the crews so frequently simply jammed the toes of their canvas topped shoes into the floor triangles for support that they wore holes in the shoes and had to repair them with duct tape.

On both Spacelab flights a video camera was mounted inside at the end of the Spacelab module opposite the entrance tunnel from the orbiter cabin. Images from the camera were transmitted to NASA ground antennas either directly or via satellite relay. Rockwell International received over 50 h of down-linked videotape covering the two Spacelab flights. Of the 50 h of video coverage, about 10 h were useful recordings showing crewmembers in action. Since the video images are in color, are accompanied by sound, and are generally of good quality, they can be a source of useful data for human factors research.

A number of researchers have begun addressing behavioral issues in low-earth-orbit spaceflight. For example, Tafforin, et al. (5), also using videotape analysis, have outlined an ethnological approach for analyzing astronaut behavior, and discovered various processes through which behavioral adaptation to weightlessness is achieved (7; for a broad discussion of ergonomics in spaceflight see ref. 8).

Study 1

On the basis of extensive qualitative viewing of the Rockwell videotapes, several aspects of crewmember behavior were identified as important components of work efficiency in the laboratory module: a) movement between work stations (Translation); b) use of one hand for stabilization (Hand Hold); c) use of the cloth foot loops provided on the floor while working (Foot Restraint); and d) out-of-control body movements (Struggle). These behaviors were quantified in order to provide estimates of how frequently they occurred and how they changed as the flights progressed. Two examples of how this relates to efficiency are: a) if the amount of translation were high we would infer that the organization of the workstation locations and task sequences was less than optimal; b) and if the use of foot restraints increased over time we could infer that crewmembers learned to make better use of them.

METHOD

Procedure:

From the 10 h of useful videotape, 80 1-min segments were randomly selected. These segments were then tested against a series of observational criteria: a) a crewmember must be fully visible; b) the 1-min epoch must not have been interrupted by a cessation in recording; and c) the quality of resolution must leave no ambiguity about what is happening. In the end, 59 segments were accepted for use in the study. While not evenly spaced, the epochs represented a sufficient cross section of the duration of both flights to allow each to be divided into first, middle, and last thirds for purposes of assessing changes over flight duration.

Once the segments were selected, the four behaviors had to be operationally defined as well as possible to produce reliable observations. Each of the first three definitions required observers to infer the purpose of an action to avoid counting inadvertent behaviors such as bumping against a foot restraint. The operational definitions were: a) Foot Restraint-time from engaging until disengaging a foot loop for stabilization or restraint; b) Hand-Hold-time from grasping to letting go for the purpose of restraint or stabilization; c) Translation-time spent traveling from one location to another from the moment restraint is relinquished until both restraint and stabilization occur at the destination; and d) Struggle-time during which loss of control interrupts work until stabilization occurs and work is again possible or time during which beginning translation orientation is lost, stabilization reoccurs, and translation resumes.

Coding: Four different raters viewed each epoch four times. One of the four behaviors being measured was evaluated during each observation by timing the behavior with a stopwatch. The inter-rater reliabilities (Cronbach's ALPHA) for the four behaviors were: Translation = 0.94; Hand Hold = 0.88; Foot Restraint = 0.87; and Struggle = 0.87; suggesting that the definitions provided satisfactory reliability.

RESULTS

The mean percent of the time spent emitting each of the four behaviors was: Translating = 9.4%; Hand Hold = 32.2%; Foot Restraint = 35.3%; and Struggle = 3.7%. This accounted for about 81% of the crewmembers' time. The remaining time was spent behaving in ways that fell outside the operational definitions of the four behaviors (e.g., simply drifting). Analysis of data over flight duration (first, second and last thirds) showed that use of foot restraints increased linearly and hand stabilizing decreased linearly over time. Struggle also decreased linearly over time. Taken together, these three changes suggest that, with experience, crewmembers learned to use the foot restraints that were provided (although not necessarily in the way the designers intended). Translating remained pretty much constant over time. Unfortunately, the crewmembers, the tasks, and the number of foot restraints and their arrangements were not identical on the two Spacelab flights studied, which limited our ability to make comparisons. However, this was partly compensated for by transforming raw scores to percentages. Foot restraint use on the second flight was 35% greater than that on the first flight, but may be explained by the fact that there were 35% more foot restraints available on the second flight.

Study 2

METHOD

Using the same procedures as those described in Study 1, the use of the built-in foot restraints was explored for the two flights for those occasions during which work was conducted at a control panel for durations of 1 min or longer. This activity required two new operational definitions: a) Control Panel Operation-when a crewmember manually operates a manipulandum on a control panel, consults an operations manual, or operates a hand tool in contact with a panel; and b) Control Panel Observation-when a crewmember restrains himself before a panel in order to observe or collect data from it. We identified 46 useable episodes of foot restraint, 18 single-foot and 28 double-foot. No inter-rater reliabilities were less than 0.87 (Cronbach's ALPHA). On each flight some foot restraints were located side-by-side, and some were staggered; that is, they were side-by-side but one was forward of the other.

The relative use of the various types of foot restraint during both short-term and long-term activities while stationary at a work station was of interest. In interviews conducted by the first author with Shuttle crewmembers, the astronauts complained that the foot loops were neither easy nor comfortable to use. We observed on the tapes that crewmembers often engaged only one of the foot loops and then stabilized themselves with one hand. We were particularly interested in the use of the staggered foot loops because they provided both lateral and longitudinal stability. Finally, we wanted to know what the other foot was doing when only one foot was in a foot loop.

RESULTS

There were large differences in the use of double foot restraints on the two flights. On the first flight, side-by-side restraints were used 81% of the time but only 30% on the second flight. On the first flight, staggered restraints were only used 19% of the time, while on the second flight they were used 70% of the time. This was probably due to the fact that there were more double foot restraints on the second flight and also more of the staggered type. Attempts at additional stabilization by some other means were much more frequent when using only one foot restraint than when using two. During the 18 single-foot episodes there were 52 instances of attempts at hand stabilizing and 135 attempts at stabilizing with the other foot. However, when using any of the double foot restraints there was only one episode of attempted hand stabilization.

The position of the non-restrained foot when using one foot loop was categorized into quarter-circle segments as being straight back, side back, side, side front, and front. The results showed that the unrestrained foot was straight back or back and to one side 62% of the time and approximately evenly divided between the other segments the rest of the time. In addition to knowing where the unrestrained foot was, we wanted to know what it was doing. We had three categories for this: Free Floating; Intermittent (periodically touching the floor or a structure); and Locked (remaining wedged against the floor or another structure to stabilize). The results showed the unrestrained foot being locked against some structure 53% of the time, intermittently wedged 40% of the time, and free floating only 7% of the time.

We conclude from these results that crewmembers often prefer to work with only one hand while using the other hand for restraint rather than using the foot loops for restraint. When they do use foot restraints, they often use only a single one and then periodically use a hand, the other foot, or both, to stabilize themselves. When crewmembers need to be more stable or have both hands free they often engage one foot loop and then force their free foot against some unintended part of the structure to gain stability rather than using two foot restraints. However, when two foot restraints are used, especially the staggered type, they provide reasonable stability but, according to interviews, are not particularly comfortable to use, especially for periods of 1 min or longer.

DISCUSSION

Given the data showing that foot loops are not used as often as expected, what might explain the reluctance of crewmembers to use them? A combination of anthropometric information and use of the time-honored human factors tool of observing precisely what the astronauts did, suggests the nature of the problem. **Fig. 1** shows the configuration of an erect human body standing in 1-G and as it appears in 0-G. In space, the relaxed human body assumes approximately the position it is in when floating in salt water and this is referred to as the *neutral body position.*

Fig. 2 gives the specific anthropometric data for the orientations of body parts in the neutral body position. In Fig. 2, notice that the angle between the shin bone and the sole of the foot is 111°, not the 90° into which they are forced when standing in 1-G. Thus, to keep one's foot in a cloth foot loop it is necessary to contract the muscles (primarily the tibialis anterior) overlying the shin to raise the foot 21° and then hold that contraction. Astronauts have told us that this is an uncomfortable thing to do. (To experience a close approximation of this, be seated, cross your right leg over your left and rest the middle of your right lower leg on top of the left thigh, and relax. Your right foot will form approximately the 111° angle with the leg that it does in the neutral body position. Now pull the foot back so that your shin and foot form a right angle and hold this position. In less than a minute it becomes uncomfortable even though the leg is essentially horizontal and the foot is not being lifted against gravity.)

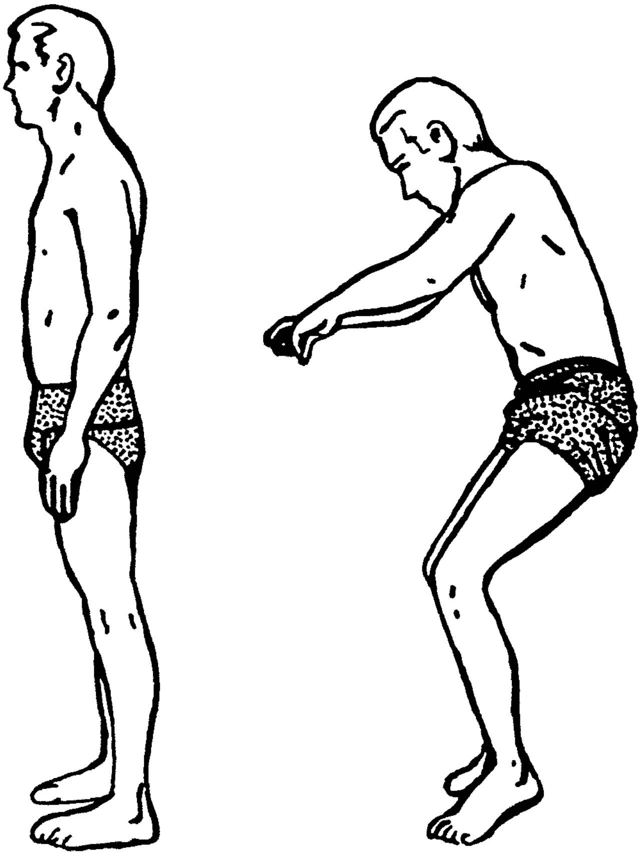

Fig. 1. Relaxed erect body posture on earth and in weightless flight (6).

A common behavior that we observed was for a crewmember to place one foot in a foot loop and then push the back part of the heel of the other foot rearward against some part of the spacecraft structure, forcing himself farther forward, and thus more tightly, into the single foot loop. Clearly, the combination of the body's orientation in the neutral body position and the pliability of the soft foot loops makes them an unacceptable foot restraint system, especially for the extended use one might expect on a space station. By combining information gleaned from our analysis, NASA debriefing reports from Skylab and Shuttle flights, and interviews with four astronauts, we have derived the following principles for the design of an adequate foot restraint for an erect crewmember.

1. Provide stability in all three axes.
2. Allow a close approximation to the neutral body position when the user is relaxed.
3. Provide gripping friction beneath the foot, not above.
4. Orient the user so that eyes and arms are correct distances from the work surfaces.
5. Allow the user some choice of distance apart, both laterally as well as fore and aft.
6. Be very reliable once engaged.
7. Be simple and easy to lock and unlock.

The findings of these studies fall into two categories: qualitative and quantitative. Qualitatively we have identified four major types of behavior: a) translating; b) working with one hand while holding on with the other; c) using foot restraints; and d) being out of control. The significance of these behaviors follows from their quantification. Being out of control nearly 4% of the time is clearly too much. Working with one hand while stabilizing with the other hand for one third of the time represents a design flaw. Using the foot restraints for only a third of the time suggests what the flaw may be. Spending nearly 10% of the time moving back and forth between the racks containing experiments might be acceptable in a lab on earth. However, given the extreme value of an astronaut's time in orbit, the data suggest that centralizing controlling functions would be wise. Finally, we determined that the cloth foot loop is an unsatisfactory long-term solution to the problem of foot restraint and suggest the characteristics of a satisfactory restraint.

At another level, an important purpose of this study was to show what kind of information could come from such an investigation, and thus demonstrate why properly designed studies of this kind should be conducted, as well as to show that this can be done with little added cost or effort to the space program.

The tapes that were available to us were not continuous recordings. Rather they were a set of segments which,

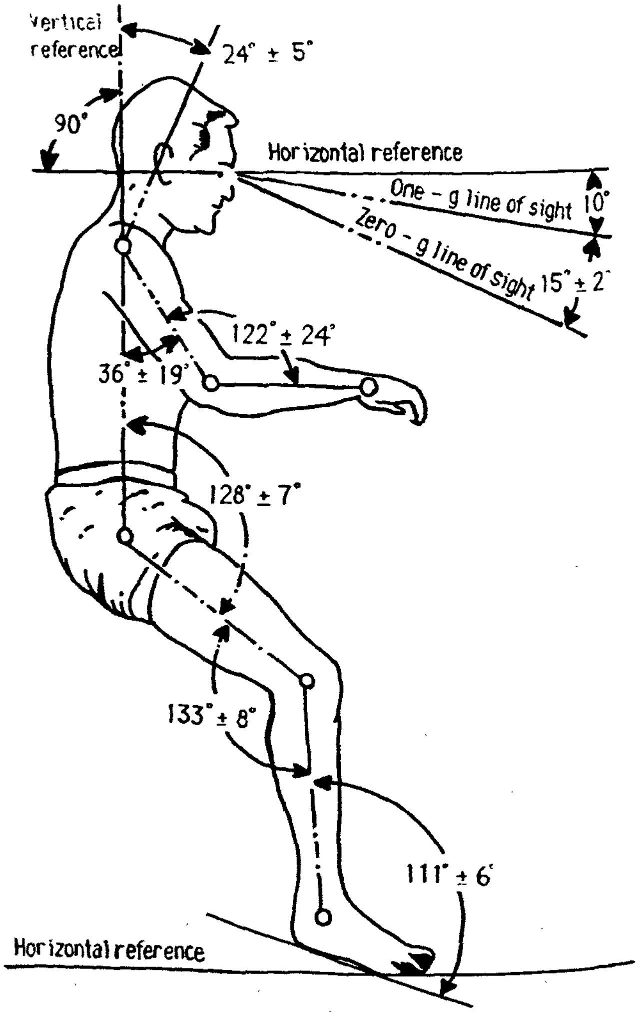

Fig. 2. Orientation of various body parts in the neutral body position (6).

while chronologically sequential, were not necessarily spaced evenly. Thus a random selection of time intervals could not be expected to be representative of all of the work time. This also meant that we couldn't do a systematic time-line analysis to show incremental changes over time. The best we could do was divide each flight into first part, second part, and third part. We did know that we had the beginning and ending of each flight but the range of the mid-portion remains ambiguous. The shortcomings of inferences that can be drawn from our results make clear how very simple experimental planning could have given unequivocal information. For instance, if different configurations of foot restraints had been equally distributed at equivalent workstations we could have determined the exact preference for each type.

The next question is: What would it take to do a well designed human factors study of crew behavior at Spacelab work stations? The answer is excitingly simple. Place a camera at each end of the module and record and down-link during *all* the time Spacelab is occupied. The reason for placing a camera at each end is to nearly always have a clear view of each astronaut. We frequently found one astronaut blocking the view of part of another crewmember. By having a continuous recording, systematic time-line studies and random time analyses could be conducted. One beauty of these studies is that they can be conducted in real-time or after-the-fact using earthbound videotape recordings made from signals transmitted from the spacecraft either directly or via Tracking and Data Relay Satellites. Preplanned experiments can be conducted and the resultant behaviors studied afterwards.

Modern cameras are very small, lightweight, inexpensive, use little energy, generate little heat and are effective across a wide range of light levels. Thus, only modest changes need be made from the way flights are conducted now, and much could be gained with relatively little added effort.

For a little more expense and operational complexity, real-time human factors research could be conducted by having human factors scientists making observations while Spacelab is in flight. If remotely controlled cameras with zoom lenses were available, observers could make more meticulous measurements of microbehaviors such as turning dials, writing or drawing, and manipulating levers. This could be done without interfering with the carefully programmed routines of crewmembers. In the past, real-time observation was not possible because of blackout periods in transmissions from the spacecraft. However, with the current satellite relay system communication blackouts are seldom a problem.

Crewmembers who have flown on the Shuttle orbiters or even in Spacelab itself do not consider restraint to be a serious problem. Indeed it may not be for the short duration (5–10 d) of typical Shuttle flights. However, when one considers the new international Space Station and the likelihood of 90-d periods in orbit for crews who will also have a wider variety of tasks to perform, the inefficiencies associated with inadequate restraint systems become serious. In this respect, the Shuttle, with its limited time in orbit, may not be a good analog of a space station. This makes human factors research, which carefully measures behaviors, all the more important because measurements can be taken on the short duration Shuttle flights and then projected to the longer durations on the Space Station.

We have demonstrated that a modest amount of useful information can be derived, after the fact, from videotapes of astronauts in action. We have then shown how thorough remote empirical research is feasible with little change to present systems. We hope that our work will serve as a model for what can be done, and that it will inspire the use of remote human factors research conducted during future flights of Spacelab and other spacecraft.

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