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OCCUPATIONAL ERGONOMICS IN SPACE

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INTRODUCTION

Ergonomics is often defined simply as the study of work. Related or synonymous terms include human factors, human engineering, engineering psychology, and others. The Human Factors Society is in the process of attempting to standardize some of these terms (*Christensen,* 1988).

Occupational ergonomics is a term that has been proposed to describe the study of the working environment and the human interaction with that environment, including the physical consequences resulting from having an improperly designed workplace. This field uses information from biomechanics, physiology, medicine, safety, and other fields. The primary goals of such work are to reduce or eliminate on-the-job hazards, reduce worker fatigue, and improve productivity. One of the beneficial side-effects of such work is that employee morale generally improves.

The failure to address and resolve problems associated with the Earthbound workplace commonly leads to such injuries as simple back pain, ruptured discs, a class of injuries referred to as cumulative or repetitive trauma disorders, crushed or severed limbs, and possibly even death.

The design of a typical workplace on Earth requires that a number of variables be taken into consideration. These can be divided into two major classes, human and environmental, as shown in Table 1.

The individual variables in each class may be further subdivided. For example, the human variable psychology may include such factors as stress and motivation. The environmental variable leverage may include friction, gravity, and handholds.

With so many variables involved, and the likelihood of interactions between them, the study of the working environment becomes a very complicated issue. However, since they can impact safety and health so significantly, consideration is imperative.

TABLE 1. Human and environmental variables typically involved in designing a safe, efficient Earthbound workplace.

Human Variables	Environmental Variables
Working posture	Pollution
Health status	Temperature/humidity
Fatigue level	Vibroacoustics
Training level	Tools required/provided
Protective clothing	Workstation/item positioning
Workload	Illumination
Individual differences	Leverage
Psychology	
Sociology	
Sex	

Humans have learned to work on the Earth over millenia. They have learned how to move about, what weights they can lift safely, and generally how to function in the 1-*g* environment. When humans begin to work in other environments, however, different rules may apply.

The routine space working environment presents some problems not found in the typical Earthbound workplace. These include radiation, intravehicular contamination/pollution, temperature extremes, impact with other objects, limited psychosocial relationships, sensory deprivation, and reduced gravity.

These are important workplace considerations, and may affect astronauts either directly at work or at some point during their life as a result of their work under these conditions. Some of the major issues associated with each of these hazards are presented in the remainder of this paper.

RADIATION

Radiation may take several forms. Probably the most dangerous in the short term is ionizing radiation. This is either particulate in nature or electromagnetic radiation composed of wavelengths much shorter than those of visible light. It may be in the form of primary radiation, as from cosmic rays and the sun, or secondary radiation from the interaction of primary radiation with the vehicle or its contents. Other types of radiation may exist from vehicular sources, such as nuclear reactors for power generation or instrumentation for crew health measures.

Ionizing radiation causes tissue damage at the cellular/molecular level. The effects range from slight illness to death in the short term, and cancer or death in the long term.

Nonionizing electromagnetic radiation is composed of wavelengths longer than those of visible light. This type of radiation is generated by power and communication systems, for example, and has been shown to have some biological effects as well (*Marha et al.,* 1971). Some commonly reported effects are abnormal offspring and cataracts. The pathology depends on the frequency and intensity of the radiation. The mechanisms for most of these effects are not yet fully known. The crew can be shielded from much of the radiation, but the tradeoff is the weight penalty the vehicle must carry.

INTRAVEHICULAR CONTAMINATION/ POLLUTION

Attempts have been made to limit the intravehicular contamination or pollution problem within spacecraft. Such pollution may consist of radiation (discussed above), chemical release or outgassing, dust, noise, microbes, and particulate debris from crew activities.

Strict guidelines have been set up for flight qualifying items and the materials from which they are made before using them in the orbiter. Presumably, similar or even more stringent guidelines will be established for future vehicles to be used in long-duration spaceflights. The exposure of astronauts to chemicals for two or three years, as in a Mars flight, might result in some long-term disability problems.

The possibility of toxic chemicals or disease-causing organisms being in the spacecraft is a serious concern. Despite rigorous sterilization techniques, a bacterium apparently survived the preparation, launch, and over two years on the Moon in the Surveyor III camera (*Mitchell and Ellis,* 1971).

Humans can be a breeding ground for bacteria and viruses. Recycled waste (including air, water, and solids) are good candidates for carrying such contamination. Just as diseases are spread on Earth, they are likely to be spread in the vehicle. The problem may actually be worse in the vehicle due to the restricted volume. These conditions can present a very stressful environment for the crew.

VACUUM, REDUCED/ALTERED ATMOSPHERE

When engaged in extravehicular activity (EVA), astronauts must wear protective clothing to protect themselves from the vacuum in space or on the Moon and a reduced atmosphere as on Mars. Several models of spacesuits have been used over the years in the American space program. All of them, however, were pressure suits to provide a breathable atmosphere in a closed system.

The primary concerns in such work are the possible failure of the suit or having the suit punctured by a micrometeoroid. The consequences depend on the internal atmospheric makeup—whether it is pure oxygen or a mixed oxygen-nitrogen composition. If a mixed composition, the incidence of one or more forms of decompression sickness may result. In either case, death is certain unless rapid assistance is available.

TEMPERATURE EXTREMES

Temperatures can vary from about -200°F to about 250°F in the region of the Earth's orbital path about the sun. When exposed to the sun, reflective surfaces are employed to reduce heat absorption. When going to Mars, which is farther from the sun and colder, it may be desirable to reduce or even eliminate the reflectivity to help keep the astronaut warm. A spacesuit or specialized clothing with internal temperature regulation appropriate for the thermal environment is required to protect astronauts from this hazard.

IMPACT WITH OTHER OBJECTS

Objects of various sizes and from various sources exist in space. As more man-made debris accumulates in orbit around the Earth, the hazard to astronauts and vehicles in Earth orbit increases. As we venture through interplanetary space to Mars, the impact hazard should decrease. The degree of hazard might increase again slightly on approach to Mars, since that planet is nearer the Asteroid Belt and may have a larger number of uncharted small asteroids near its orbit than does the Earth.

Impact with any object of significant size could have disastrous consequences for a spacecraft and its crew. If the impact resulted in puncture of the vehicle pressurized volume, the crew could be exposed to a variety of hazards such as decompression sickness and flying debris. On a flight to Mars, even presuming repairs to and essentially full functional recovery of the vehicle were possible, the loss of air and other consumables could be critical if an inadequate supply remained to successfully complete the trip. There will be no resupply like there can be in Earth orbit.

The risk of such an event depends on the mission. In low Earth orbit, the larger debris particles are tracked. If the crew could be warned in time to make a course adjustment, the ship may avoid damage. Based on our experience with many vehicles having been sent into interplanetary space, the risk is probably quite low. However, previous vehicles have been relatively small craft, and the size of a manned vehicle to Mars will be much larger. One must presume that as the vehicle dimensions increase, the chances of impact also increase. Our ability to detect and avoid objects in interplanetary space is unknown.

For an astronaut working outside the vehicle, an outer garment was designed for spacesuits to provide some micrometeroid protection. This outer garment is intended to stop the smaller objects and prevent them from penetrating the pressurized portion of the suit.

PSYCHOSOCIAL RELATIONS

The crew will form their own microsociety in space. There will be separation from loved ones, and from the Earth itself. The crew will be confined to the spacecraft or the base much of the time due to the hazards of working in the space environment. They will have to be a compatible group of people.

On a Mars flight, the crew won't even be able to see the detail of Earth for much of the trip. Thus communications with those back on Earth will be very important in maintaining morale, health, and productivity. Yet the communication will be hampered by long delays.

Crew selection and training will be very important issues in long flights. Some personality types will not be suited for such missions.

SENSORY DEPRIVATION

The problem of sensory deprivation or reduced sensory input in space is largely an unknown. During brief visits to the Moon, the problem with reduced stimulation of the vestibular senses under the lower gravitational pull may have been a determining factor in the astronaut's gait. Many of the astronauts developed a peculiar hopping gait for locomotion because it was deemed effective in maintaining their sense of equilibrium (*Graybiel,* 1974).

Other effects may only show up with extended stays. Humans' current sensors have developed during their evolution on Earth. An interesting question may be raised as to whether this sensory system will change in sensitivity or other ways over time in different environments.

In low Earth orbit (LEO), microgravity can be achieved by existing in a continual state of free-fall. But the gravitational field of Earth has not been reduced to any great degree. That will happen only when humans are a significant distance away. In interplanetary space, those gravitational accelerations besides the sun may be insignificant. Do humans have some sense that detects gravitational fields?

The Moon and Mars have no significant magnetic field. Some data exist that indicate that animals, given a choice, will escape from or avoid a magnetically shielded environment. Would there be something aversive to working on the Moon or Mars under such conditions?

Many of our biological rhythms appear tied to sensory cues from cyclic activity related to Earth. Our circadian rhythms are tied to the length of the Earth day. The 24-hour cycle does not exist on the Moon nor apparently elsewhere in our solar system, although Mars has a rotational period close to that. Humans may have to artificially maintain certain rhythms to avoid "jet lag" types of problems.

REDUCED GRAVITY

The microgravity condition presents a number of problems to humans.

On short flights to LEO, consisting of a week or less in length, the primary concern is the space sickness or space adaptation syndrome that some astronauts experience. When it occurs, the symptoms can often be treated with drugs.

Due to lack of compression of the spine in microgravity, an increase in height occurs. This has necessitated use of a correction factor in sizing spacesuits so that the astronaut will be more comfortable working outside the spacecraft.

A cephalad fluid shift and overall fluid loss from the lower body occurs. Thus far, these appear to have no long-term health effects. These effects are countered by having crewmembers drink a lot of fluid prior to deorbiting.

On the longer-duration flights, certain physiological problems occur. These include a cardiovascular deconditioning, bone demineralization, and skeletal muscle tissue loss.

The cardiovascular deconditioning does not seem at this point to have any long-term effects on return to gravity, given that adequate provisions such as increased fluid intake are made for the return. Additional long-term studies should be done to verify this, however.

Until countermeasures were introduced, the Russian cosmonauts were taken off their return vehicles in stretchers after extended periods of microgravity. Apparently the orthostatic intolerance due to cardiovascular deconditioning in space was sufficiently severe that the returning cosmonauts could not stand on their own for a few days without feeling faint.

A major long-term concern about extended microgravity exposure is that of bone mineral loss. This phenomenon was first recognized in the Gemini flights, then confirmed with animals and humans in Russian flights (*Parin et al.,* 1975). The amount of reported bone loss in those early flights ranged up to about 15% in eight days. However, there is debate today about the accuracy of those data.

In later flights, including Skylab, better analytical techniques and an exercise countermeasures regimen were implemented. As a result, the reported bone losses were significantly reduced. The Russian flight data indicate variability among their cosmonauts, but with an average of about a 5% loss during a six-month flight (*Stupakov et al.,* 1984). Some preliminary information indicates that Yuri Romanenko, the Russian cosmonaut who spent 326 days in space, suffered only about a 5% bone loss.

In the only post-mortem study performed on cosmonauts, it was noted that the osteocyte lacunae were unusually large (*Nicogossian and Parker,* 1982), probably indicating bone loss.

Depending on one's definition, this bone loss may be similar to osteoporosis. One of the consequences of osteoporosis is that bones become brittle and more subject to fracture. Women are normally considered to be at greater risk for this disease, but recent evidence indicates that men are not immune. There appears to be a lag period of about 10 years for men (*Alvioli,* 1987).

Even if the astronauts return safely to Earth after a long-duration mission, there is some uncertainty about long-term occupational disability aspects. For example, the astronauts may experience premature fracturing later in life.

The skeletal muscles also suffer in microgravity. Since there is no need to retain a standing posture against gravity, the postural muscles of the leg and back are underused and atrophy. An initial report indicates that Yuri Romanenko lost 15% of the muscle volume from his legs (*Covault,* 1988).

Part of our lack of understanding in these areas is due to the techniques used in obtaining this type of information. Dual photon absorptiometry has been used recently as a better quantifier of bone mineral loss; a computerized tomography scan might provide better results, and for the whole body, not just one or two bones. The Jet Propulsion Laboratory (JPL) is currently working on a magnetic resonance imaging (MRI) device to quantify the amount of tissue loss (*NASA,* 1987). While this testing will expose the body to additional radiation, such research must be carried out to learn exactly what the effects of living in microgravity are.

Possible measures to counteract the bone mineral and skeletal muscle tissue losses include exercise that simulates working against the force of gravity, centrifugal force (usually referred to as artificial gravity), and what might be called "drug" use.

Exercise has been shown to reduce bone losses in the studies above. To do so, though, takes about two hours from each crewmember's day. This has a major negative impact on crew productivity.

Is an exercise countermeasures program alone adequate to prevent osteoporosis? What if an astronaut or cosmonaut sustains a fracture or becomes ill for a long period of time and is unable to exercise? Such a development could be a critical situation for that individual and a major setback for the mission. Without exercise, the crewmember would become subject to an even greater amount of bone demineralization. Should another mechanism be provided to assist in preventing bone loss?

The idea of a variable-gravity Earth orbital station has been proposed by the Sasakawa International Center for Space Architecture (*SICSA,* 1988). It was named the Variable Gravity Life Sciences Facility (VGLSF), and would be a rotating platform that provides centrifugal force of different magnitudes, depending on the distance from the center. A similar concept of rotating at least a portion of the vehicle has been discussed for reducing the bone mineral loss on long missions.

The use of drugs to prevent osteoporosis is a possibility, but most of them have undesirable side effects. Estrogen would obviously not be a good candidate for men. Other potential drugs might include calcitonin (*Alvioli,* 1987) or fluoride (*Posen,* 1985).

The important ergonomics and mission questions are, then, what effects will these bodily changes and the working environment have on astronauts' ability to carry out their assigned tasks in space or on the Moon or Mars? They could be fairly significant when all the variables are factored in.

Interpolation or extrapolation of human performance from current Earth-based data or may not be accurate in the exploration of other bodies. For example, a man who can lift 100 lb on Earth probably will not be able to lift 600 lb on the one-sixth gravity of the Moon, especially when encumbered by a 200-lb spacesuit.

One known extrapolation inaccuracy occurred when the astronauts arrived on the Moon. Preflight Earth-based simulator data had indicated they might walk with a much longer stride than was normal on Earth, and bound much higher. As indicated previously, many of the astronauts developed a completely different mode of locomotion—a gait resembling hopping or bounding.

An interesting result was noted from a preliminary analysis conducted by the author of some of human's potential capabilities on various solar system bodies that we might expect to visit within the next few decades.

Theoretically, Phobos's gravity and escape velocity would permit the first human-powered satellite launch from that moon of Mars. Whether this could be actually done or not will depend on the condition of the astronaut after a flight from Earth, spacesuit mobility, what kind of leverage an astronaut could achieve, the mass of the object, etc. Will this extrapolation prove to be valid?

In analyzing the work to be done in space or on the Moon or Mars, several classes of tasks can be stated now with reasonable certainty. Some of these have been summarized in *Hall* (1985), but many other types of tasks would have to be performed in constructing a Moon base, for example. Specific aspects of many of these tasks will have to await development of the actual hardware to be used.

What might happen to an individual's strength capabilities is important for working safely in space. Does a 15% loss in muscle mass correspond with a 15% decrease in strength? Considering both the bone and muscle loss, what decrease in safe working strength does it represent? The relationships aren't known yet.

The National Institute of Occupational Safety and Health (NIOSH) has produced a guideline for a specific type of lifting task on Earth (*NIOSH,* 1981). Similar guidelines could be developed for other types of tasks.

In this guideline, the authors define an action limit (AL) and a maximum permissible limit (MPL). The AL is the recommended weight limit for lifting under the given working conditions. This limit is designed to prevent injuries in the average healthy person. Lifting above the MPL incurs an unacceptable risk of injury.

Equations have been developed to permit calculation of AL and MPL values. These values are based on the initial and final positions of the object to be lifted, its mass, and the frequency with which the task is performed.

To generalize such guidelines to space, some additional variables have to be considered. These would include the gravitational field strength under which the work is being carried out, the clothing characteristics (i.e., a spacesuit or pressure suit), the conditions and time spent in microgravity prior to working on the task, and many of the other variables given in Table 1.

An orbiting laboratory similar to the VGLSF may be used to estimate human's capabilities under a range of gravitational accelerations and other conditions before going to the Moon or Mars. By proper positioning aboard such a vehicle, it could be used to simulate a variety of specific gravitational fields.

The restriction caused by the spacesuit is a major factor in working in space. The astronauts' reach and strength capabilities are greatly reduced and metabolic rates are increased.

We have begun to quantify the reduction in reach capability with the current shuttle spacesuit in NASA's Anthropometry and Biomechanics Laboratory (ABL) at the Johnson Space Center.

The percentage volume of one-handed reach capability in the suited condition is only about one-fourth to one-third that of the unsuited capability (*Stramler,* 1986). The two-handed reach capability, which simulates a task requiring two hands working closely together, has a much greater reduction. In the case of an approximately 50th percentile stature female subject, only about 3% of the unsuited reach volume was achieved.

Another study performed in the ABL was to determine the torque that spacesuited astronauts were able to produce in a simulated space station strut assembly task (R. Lewis, unpublished data, 1987). Under the conditions of the experiment, not unreasonable for actual construction in orbit, the maximum torque output was only about 11 ft-lb. This type of task, done repeatedly, especially in a spacesuit, is clearly a potential candidate for producing carpal tunnel syndrome, one of the repetitive/cumulative trauma disorders.

As shown in another study supported by the ABL, the metabolic cost or physical workload increases while working in a spacesuit (e.g., *Dierlam,* 1984).

Greater endurance can be achieved if the oxygen consumption for routine effort vs. maximal effort (the VO_2/VO_2max ratio) is kept as low as possible for a given task (*Kamon and Ayoub,* 1976). Under such conditions, the astronaut will require less rest, i.e., be more productive in a given time. Keeping this ratio low also tends to reduce the chances of injury (*Chaffin,* 1975).

One might be tempted to think that the reduced gravity in space or on other nearby bodies would tend to decrease injuries—that working in space is easier than in Earth's gravity. Work in space to this point has indicated that, given a proper set of restraints and mobility aids, it is much like work on Earth. This may not always be the case, however. In the case of long stays on the Moon or long-duration flights to Mars, for example, the greater physical effort required to manipulate the suit and at least some minimal amount of osteoporosis and muscular atrophy may actually increase the risk of injury.

Medical care will be limited in space. Medical facilities will probably resemble a small clinic or even battlefield conditions more than a hospital. Thus injuries should be prevented rather than treated.

It is also important to remember that when in space, the vehicle/base becomes the workplace, home, and recreational center all in one. Many accidents or injuries on Earth occur in the home or while playing. There is little reason at present, aside from the restricted habitable volume, to believe the situation would be any different in space.

There has been a great deal of talk about using robotics to complement humans in space, if not replace them. The use of robotics seems appropriate under certain conditions. However, what the activities involving manned exploration and working in space will allow in terms of robotics remains to be determined. Certainly the potential is there to provide relief from repetitive activities and those activities that may lead to human injury.

The only really definitive means of determining what humans can do on another body such as the Moon or Mars or in microgravity is to be there and conduct the tests. We have much to learn as we begin to explore these environments.

The goal of such work should be to establish some guidelines for use under those conditions and on other bodies in the solar system such as have been put forth by NIOSH for Earth-based work. Some initial guidelines might be the following: remain below NIOSH AL equivalent; minimize VO_2/VO_2max ratio; minimize microgravity exposure duration; minimize radiation exposure; improve spacesuit mobility; reduce spacesuit mass; use the strongest people available; and use robotics when practical.

There will probably be several tradeoffs in following these guidelines. Some actually oppose others, given current technology. For example, the astronaut needs a spacesuit with high mobility and the lowest possible mass to work most productively. Yet to provide better shielding from radiation, more mass is required in the suit. What the tradeoffs will be are uncertain at this time.

Once humans have been to the Moon, Mars, and Phobos to perform some testing on their performance capabilities under these gravitational accelerations and other conditions, we should have the groundwork for predicting their working capabilities on any body in the universe that we might explore.

The fact that there are significant problems to be overcome shouldn't prevent humans from exploring other planets and ultimately the universe. We will find the means to overcome these problems. There were hardships in exploring the Earth, but we accepted them and conquered it. We will do the same in space.

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