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AN INTRODUCTION TO SURFACE-FREE BEHAVIOUR

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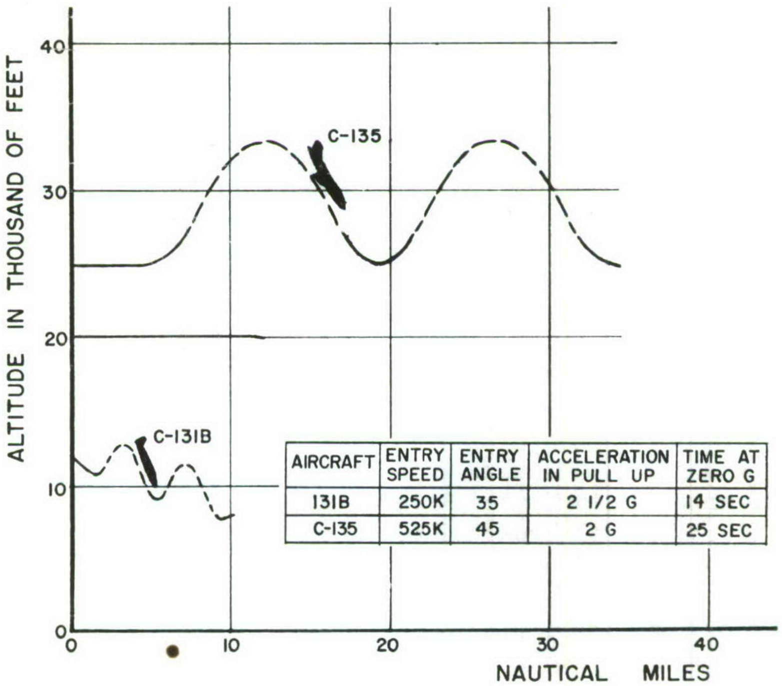
The motions of the weightless free-floating worker are discussed. Study techniques include physical analyses of the motions, inflight validation of the analyses, and mathematical projections of probable orbital motions. Sensations arising from these motions are also discussed.

The motion freedom of the unencumbered surface-free subject revealed many motion restraint and augmentation requirements and such devices as lifelines, adhesive footgear and self-manoeuvring units are required to limit and control his motions. The effects of transient weightlessness on sensory, psychomotor, and motor functions have revealed minor effects but the perception of the postural vertical and the response of the circulatory system to the return of positive gravity are considered important problems.

§ 1. Introduction

This paper reviews some of the problems of motion and sensory-motor performance by weightless men in the orbital situation. Large cabin-volume aircraft flying short term weightless manoeuvres (Hammer 1961) are used to suspend subjects free from all surfaces and offer them freedom of motion. Details of the manoeuvre are shown in Fig. 1.

The approach adopted represents an open-tight methodology as Christensen describes his position on 'loose thinking', i.e., 'Our approaches to systems research are in danger of becoming stereotyped too soon ; we may be insisting



AIRCRAFT	ENTRY SPEED	ENTRY ANGLE	ACCELERATION IN PULL UP	TIME AT ZERO G
131B	250K	35	2 1/2 G	14 SEC
C-135	525K	45	2 G	25 SEC

Figure 1

on a strict operationalism too early in the game' (Christensen 1962). As Bateson summarized, '... the advances of scientific thought came from a combination of loose and strict thinking and this combination is the most precious tool of science' (Christensen 1962).

The author had a facility capable of producing a new and unexplored surface-free environment and was faced with the problem of selecting short term behaviour samples worthy of study. A loose problem-search approach (Phase A) with two 'tight' analytic phases (B and C) evolved. The aircraft was used to isolate important behavioural responses in Phase A, and later to validate phase B and C analyses of these same responses. In phase B physical models were used to obtain kinematic understanding of the forces, masses and response relationships and the ranges and rates of motion behaviours were explored. The author knew that free-floating in the rear of an aircraft was not environmentally equivalent to soaring in outer space. But this gap could be partially bridged in Phase C by mathematically projecting the behaviours into orbital motions.

This loose-tight three phase approach had two results. First, it required an interacting group of engineers, psychologists and anthropologists. Second, and most important, when the three talents became simultaneously involved, the interactions forced the generation of new ideas. For example, tethered tumbling in the aircraft suggested analyses of the desirable body attachment points. This analysis required an understanding of the stability and free-axis properties of a weightless flexible free-Form, such as man. The stability study suggested the need for an understanding of tethered trajectories and the trajectories may depend upon the determination of the desirable damping characteristics of the lifeline.

§ 2. Relaxed Posture Without Motion *

Observation of changes of the limb positions of harnessed and free-floating subjects has generated interest in determining if a characteristic free-floating, relaxed posture is assumed by the human body during periods of zero gravity. The following comments of subjects under 0-g conditions point to this possibility: 'Arms and legs float up. Arms and legs would rise up, especially arms.' 'Body weight seemed removed from pelvis and buttocks and traversed downward to legs.' 'I believe I went into a vertical sitting position after pulling on handline.' 'I'm comfortable in any position under zero-g.' 'Relaxed posture is bent over, arms and legs akimbo. I felt like I might be slightly doubled up.' 'My arms and legs felt loose.'

Experiences of these men indicated that there is a tendency for the appendages to assume new attitudes. Seated observers have commented that their feet and arms tend to rise off the floor and arm rests and that they must consciously maintain their extremities in contact with their supporting surfaces. Free-floating subjects have commented, on numerous flights, that they inadvertently assume an attitude resembling the seated position when they relax. Drawing on these experiences, an attempt is made here to describe a generalized body posture which may actually be assumed under these conditions.

* This section was contributed by Kenneth W. Kennedy, Anthropology Branch, 6570th Aerospace Medical Research Laboratories.

In any position assumed by a weightless, free-floating, lightly-clothed man, there would be a state of angular equilibrium reached between body segments. For example, muscles which normally function to flex the forearm would likely reach a position of equilibrium with those which normally extend it. Assuming that the mass and tonus of each of these sets of muscles are equal, which they are not, the position of the forearm could be expected to be very close to the midpoint of its angular movement, all other influences being equal. But because the muscles which flex the elbow (biceps) are usually of a greater mass than those which extend it (triceps), the forearm would tend to relax at a position farther towards the extended position than the exact midpoint. In more general terms, then, the relaxation of a muscle or muscle complex which has a larger mass than those which normally oppose it would be expected to cause the segment to move farther than the midpoint in the direction of the opposing smaller mass.

From these considerations it is assumed that individual body segments will find their positions of equilibrium near the midpoints of the ranges of movement of their joints. The mean ranges and midpoints of joint movements are listed below :

Joint	Movement	Range	Midpoint
Shoulder	Flexion and Extension	249°	63° Flexion
	Adduction and Abduction	182°	43° Abduction
	Medial and Lateral Rotation	131°	31° Medial Rotation
Elbow	Flexion and Extension	142°	71° Flexion
Hip	Flexion and Extension	113°	56° Flexion
	Adduction and Abduction	84°	11° Abduction
	Medial and Lateral Rotation, Prone	73°	2° Medial Rotation
Knee	Flexion and Extension	113°	56° Flexion

Figure 2 shows the configuration resulting from a plot of these angles.

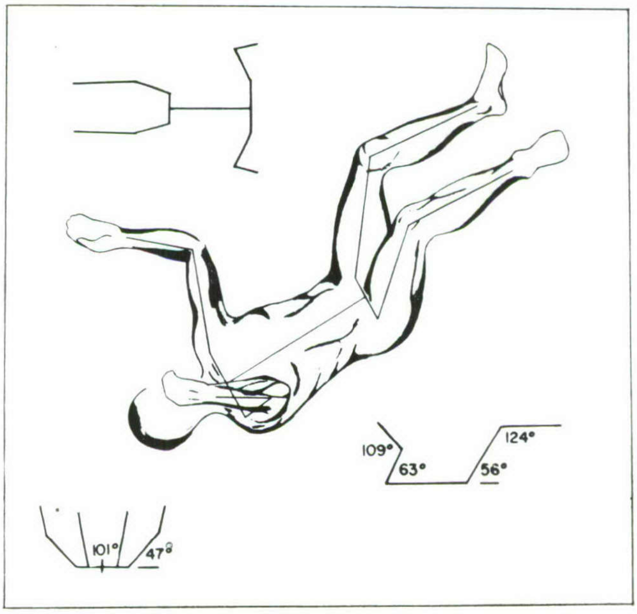


Figure 2

The characteristic relaxed posture under a condition of weightlessness continued for a long time is not yet known, but it might be anticipated that there would be some alteration in segment-to-segment relationship due to loss of muscle tone and eventually to atrophy resulting from reduced usage.

§ 3. Linear Motions

3.1. *Soaring*

During zero g aircraft flight, subjects pushing off with legs attained velocities of approximately 10 mph. All subjects suffered slow, undamped rotations because of their inability to precisely programme their thrust through their centre of mass during launch. Once free of the bulkhead, the subjects had *no position control* and *poor attitude control* as their trajectory was determined solely by their launch.

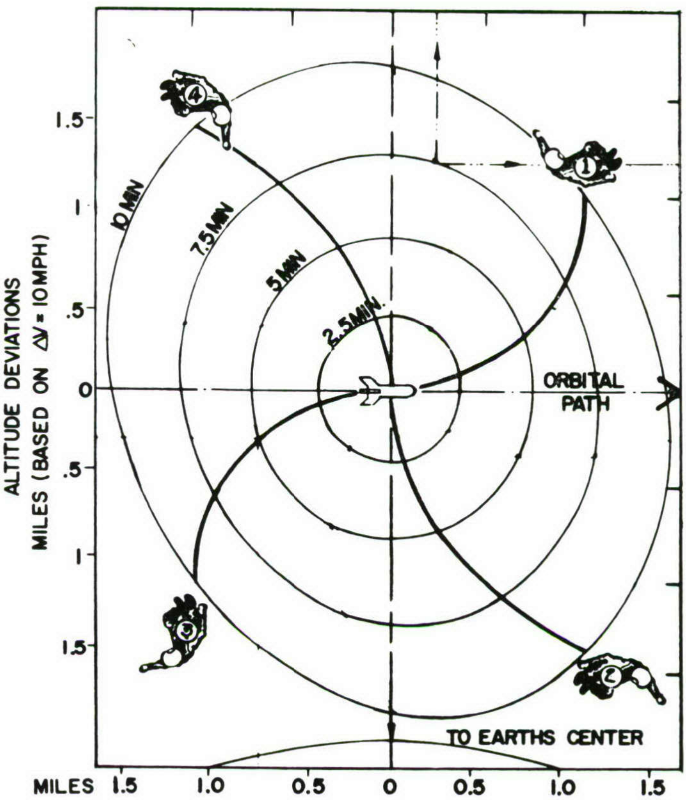


Figure 3

Orbital projections of these single-impulse coplanar launches were originally computed by Perret for man in space, and Fig. 3 shows his flight path relative to the vehicle from which he has departed. A forward launch will position him over 1 mile ahead and 1 mile above the vehicle after 10 minutes of soar. After one earth orbit of about 90 minutes, he would find himself 47 miles directly behind his ship. The complexities of soaring can be appreciated when one notes that an earth directed soar will find the subject 11 miles in front of the vehicle after 45 minutes and arriving back at the ship from *above* after 90 minutes ; and if the subject soars in any direction other than straight up or down, he will never return to the vehicle ! These ideal single-impulse trajectories show the potential trajectories for accomplishing short-orbital transfers between vehicles (Mueller 1962) and the awesome results of an inappropriate launch.

Men will be able to soar within a large vehicle just as crew members now walk on walkways. Handholds or handrails will serve as anchor points. The space required for such movements is being studied.

3.2. *Walking*

Without some restraining devices, the normal walking gait will propel the weightless subject from his surface. Several varieties of adhesive footgear (Fig. 4) have been developed such as permanent magnet sandals, electromagnetic shoes, and adhesive cloth (Velcro) shoes. These special aids force

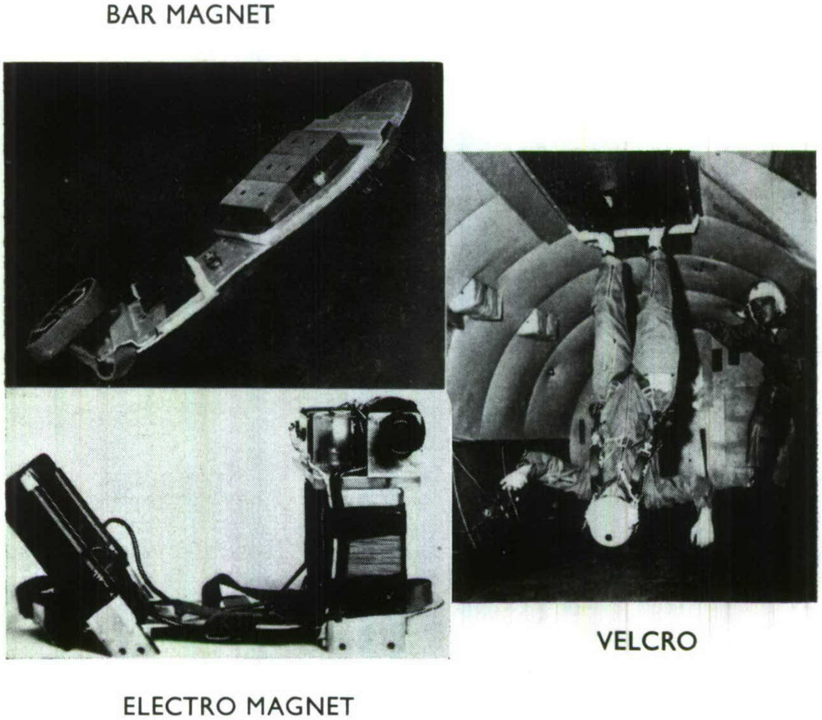


Figure 4

an abnormal walking gait on the subject because, in the act of pulling his foot loose, he pulls his body toward the retracting foot and introduces a pronounced roll of the body. Also starting and stopping introduces a pendulous pitch because of the walker's requirement for controlling his entire accelerating body mass by the ankle muscles without the aid of a body-to-surface directed force.

A *foot-is-down* concept of orientation was noted by subjects who were not rotating, regardless of their position within the aircraft, and floors and ceilings were perceived as ' a collection of surfaces. ' The operator perceives *himself* rather than his *environment* as the focal reference for partial orientation, due, apparently, to lack of stimulation of the inner ear balance mechanism accompanied by the continued stimulation of deep muscle receptors.

Much has been written about the advantages of living on the inner rim of a spinning space station. The creation of artificial gravity by rotating a space vehicle introduces the interacting conditions of fractional gravity (between 1 and 0 g) and Coriolis effects caused by the crew's movement on a moving surface. The lower limit of induced g that can be used for successful walking has been established near 0·2 g, and an upper practical limit near 1·0 g (Loret 1961). In both of these, the value has been set so that by walking against or with the rotation of the vehicle, the +1·0 and +0·2 g limits are not violated. To minimize the Coriolis effects leading to canal sickness an upper limit of 0·4 rad/sec was placed on angular velocity. Engineering considerations such as structural loads and material stresses have described the upper limit on radius of rotation. Physiological considerations of the ' gravity gradient ' or the difference in g between the head and foot of a standing person, has been established at 0·5 g, therefore establishing a lower limit on radius of approximately 40 feet. Studies of operator limits within radial spokes of a rotating station are now being conducted.

3.3. *The Use of Tethers*

The soaring paths have shown the need for saftey lines which will restrict the subject's freedom during soaring. When slack, the line can move within an ellipsoid as shown in Fig. 5 and the man has unrestricted movement except where this would result in his becoming entangled with the line. He can minimise the risk of entanglement by *moving* his point of attachment to his desired axis of rotation (Schlei 1961).

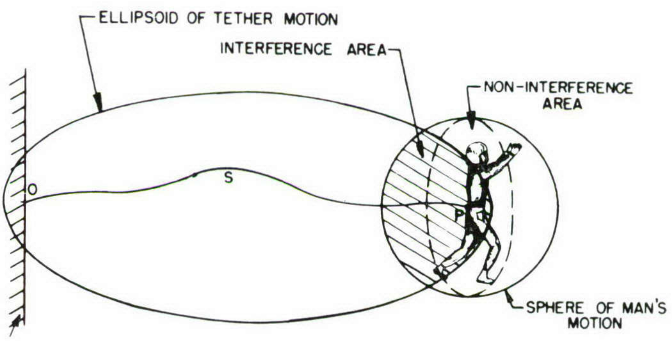


Figure 5

The crew member will find some astonishing motions at his disposal on the outside of a rotating space station (Kulwicki 1962). Tethered with a lifeline to the spin axis (centre of rotation) of the vehicle to prevent him from being thrown into space, he can achieve radial displacement by merely *varying the length of a taut line.* If his feet remain in contact with the surface, his motion will be linear and if he removes his feet, his motion will be curvilinear. Motion to achieve angular displacement can be achieved by *keeping the line loose and removing body contact* from the surface of the station. His motion will be linear and will be the result of tangential velocity from the last point of contact. All that is necessary to stop angular displacement is to pull the tether taut. Problems involved in this type of locomotion will include keeping a stable attitude, coping with Coriolis and tidal forces, developing a usable tether line,

Figure 6

non-coplaner motion due to a variable tether angle with the station surface, canal sickness effects due to the linear motion of the station itself and the stability problem of alighting on a rotating surface. Kulwicki is investigating the latter problem by studying the response of subjects jumping upon a moving treadmill.

Motion along a lifeline strung within or between vehicles will make guided

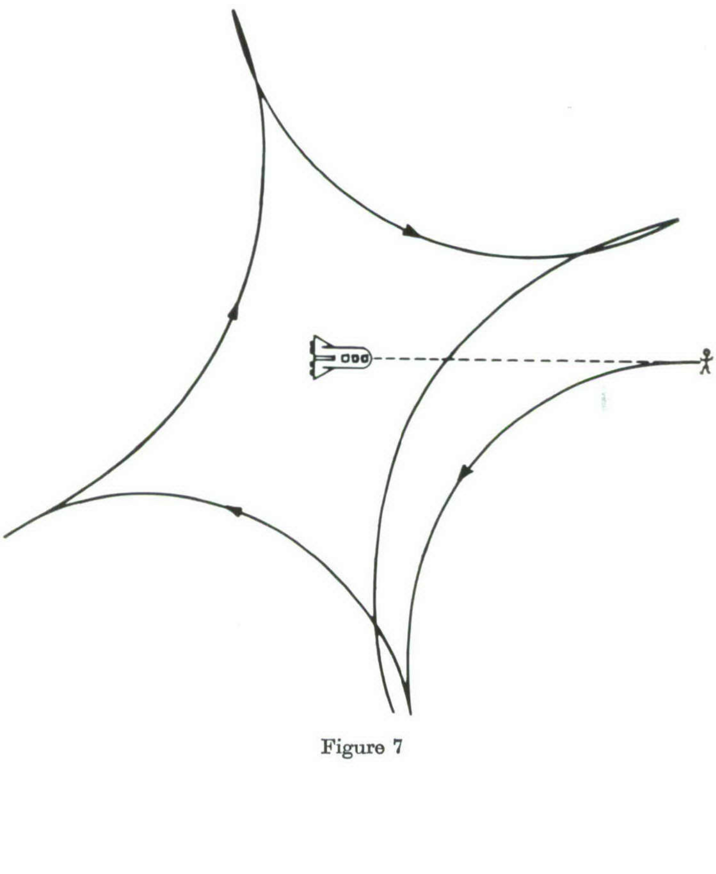


Figure 7

trajectories possible. In our studies subjects grasped a 3 in ring and soared along a stretched nylon cord after using hand or foot launches as shown in Fig. 6. Position control was easily maintained, but attitude was erratic. In Fig. 6 the author has thrown a ball above the subject in order to judge Coriolis effects on soaring subjects in a rotating aircraft ; foreward moving masses tend to move toward the ceiling (Mueller 1962).

The movement of a man tethered immediately ahead of a vehicle's path reveals the unusual orbital motions which occur in space (Fig. 7). If he pulled on the line and it remained slack, he would immediately lose altitude because of his decreased orbital velocity and bounce toward the vehicle when his line tightened. He would continue arcing (and tumbling at the end of the line) as shown in the figure until he applied other forces to the line (Mueller 1962). These trajectories reveal the need for determining the desirable damping characteristics of the lifeline (a rigid line may continuously 'bounce' the operator) and introduce possible new flight paths for the operator. Whitsett's (1962) analyses may help determine optimum number and points of attachment of tethers to the body.

§ 4. Rotational Motion

Although the worker cannot move himself linearly (without expending mass) when between vehicles, he can turn himself by carefully moving his arms and legs in predetermined motions. Based on a stick model man (Fig. 8 left), nine manoeuvres have been proposed for achieving self-rotations through body manipulations (Kulwicki 1962).

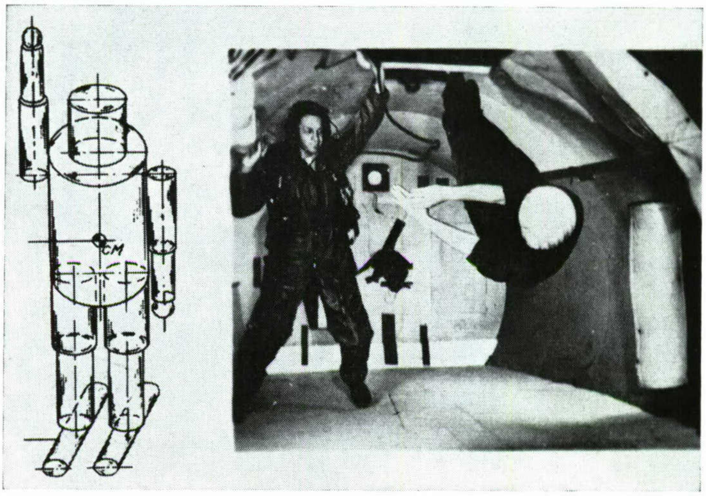


Figure 8

The linear and angular momenta of the static worker are zero. The body is flexible, however, and capable of generating internal forces and moments. A subject can rotate his arms at the shoulder (Fig. 8 right) and his arms will have an angular momentum ; however the rest of the body will rotate in the *opposite* direction because the total body angular momentum must remain at zero. When he stops rotating his arms, his body rotation stops. By adding mass to his hands, he can increase his body rotation velocity. If he were spinning, he might be able to rotate his arms to stop the spin, but he would resume spinning as soon as his arm rotation stopped. The rotations are inefficient because of *impure rotations* (coupling motions about other axes) and demand *much energy expenditure* for small amounts of body rotation.

A dynamic (conservation of linear and angular momentum) model of the flexible weightless man is needed to bridge the gap between anthropometric data and the equations of motion needed for engineering design. Whitsett has approximated the mass distribution, centre of mass, moments of inertia and degrees of freedom of a human being (Whitsett 1962). The model can be used to study problems of stability, axes of rotation (which are unlimited with a flexible form), body responses and tumble behaviour. One method being used to validate the model is initially to spin a subject about one axis and measure the magnitude and torque a man can exert from the resulting reaction of a change in posture during a spin. The tumbling subject can reduce his rpm about his vertical (head to foot) axis from 14 to 5 rpm (a ratio of 2·5 to 1) in 0·4 seconds after assuming a spread-eagled posture.

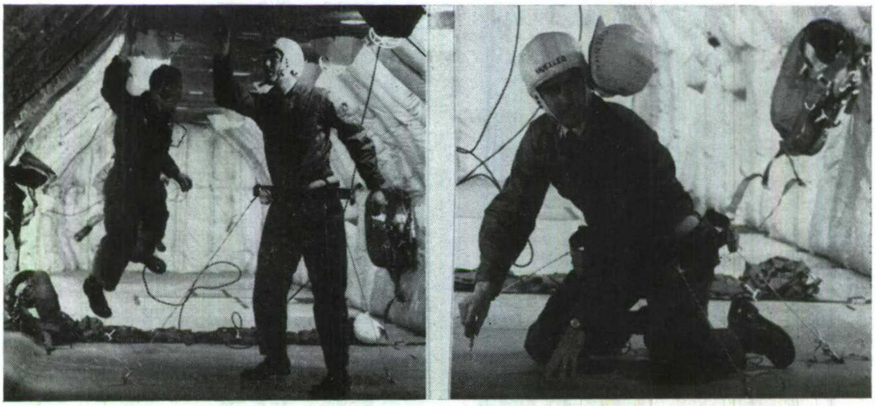


Figure 9

For tasks involving limited movement a spring loaded tie-down technique which tethers the subject to the surface but allows the body to turn is being studied. The subject wears a belt freely rotating within another belt and this system is suspended by lines attached between the surface and inertia reels on the belt as shown in Fig. 9. With equal tension in all lines, the only force on the man will be toward the space craft which he can oppose by standing or kneeling on the surface (Schlei 1961). The subject may vary his alignment to the surface, for example, by lying prone and using one stomach-to-surface line, he would still retain freedom to turn.

For more intricate tasks to be performed between vehicles, the worker may require a back-packed stable platform (Fig. 10). A device to offer man tumble recovery, controlled rotation, and inherent stability properties is currently under study. It uses two gyroscopic elements carried in a back-pack. With these, stability can be obtained about three axes since a gyro element has

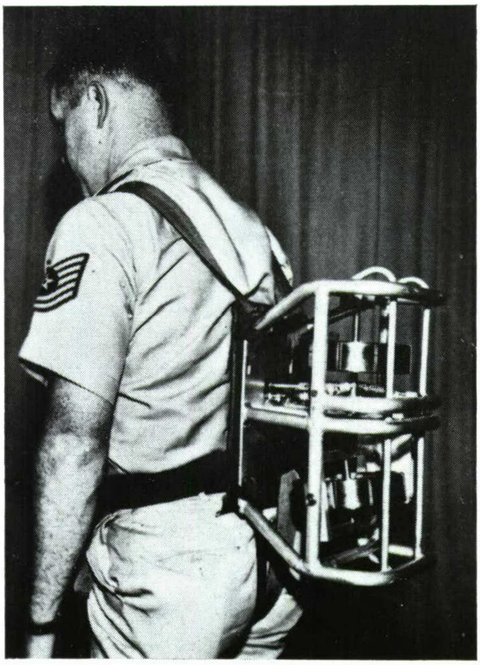


Figure 10

inherent stability about two axes. Purposeful rotation can be achieved by exerting torque on a wheel axis and thereby precessing (rotating) the entire system.

4.1. *Self-Manoeuvring Units*

A man can assemble prefabricated units, tow supplies and even move vehicles with a propulsion unit offering rotation and translation motions. Several units are being developed.

H. T. E. Hertzberg of the Aerospace Medical Research Laboratories originated and assembled the first single-nozzle, pistol grip, propulsion unit (Fig. 11). His tests showed that the system was moderately successful within the limitations of the aircraft's volume. Velocity from a 1-second blast (using 3000 pounds/in^2) was about 6 feet per second ; directional control on first try was correct ; and it was possible to stop in space and back up. The proper alignment of thrust through an oscillating centre of mass, directing the thrust precisely in the direction opposite to that of the desired travel and inadequate deceleration control were the major problems.

A two-hand controlled, compressed air, self-manoeuvring research unit developed by the Bell Aerosystems Co. was developed for studying optimum nozzle placement and thrust requirements (Flexman 1963). A space Self-Manoeuvring Unit (Fig. 12) was designed and flight tested by the Chance-Vought Aviation Co. It is a self-contained propulsion and life support system, weighing approximately 150 pounds, which straps to a pressure-suited man's back and provides him with the means to manoeuvre and perform useful work outside his space vehicle (Griffin 1962).

Figure 11

Severe limitations may be placed on the rates of the translatory motions because of *curved* flight paths and poor *rate of closure* information. The curved trajectories will produce confusing line-of sight problems and dangerous closure rates will produce deceleration problems (Simons 1960).

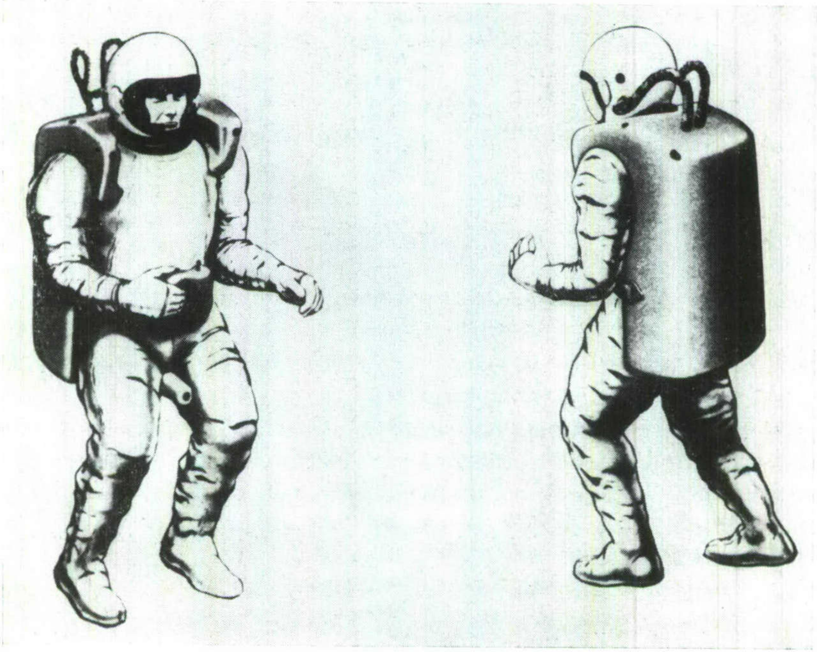


Figure 12

§ 5. Motion Sensations and Performance

Gerathewohl (1956) states that, ' There can be no doubt that the differentiation between ' sensation ' on the one side, and ' performance ' on the other side, is an artificial one because both factors are so closely linked together and interrelated that any separation can serve as a working hypothesis only. It is mainly for the sake of a schematic classification of symptoms that we confine ourselves to the treatment of the ' subjective ' or personal experiences of weightlessness. Thus, psychological and somatic effects of weightlessness may stem from the same source ; and they may affect the well-being of the individual as well as his task performance. ' What sensations will our worker have when he departs from his familiar surface and moves into the black void of space ?

In one attempt to study these sensations (Simons 1962), the NASA astronauts, deep-sea divers from the U.S. Navy New London Diving School, and USAF personnel recorded their sensations as they floated free or made various movements in the aircraft. Some of their sensations were categorized as follows :

(a). *Exhilaration of freedom from surface*—subjects who were not annoyed by motion sickness almost invariably smiled and laughed, appeared to enjoy their soaring and reported symptoms of euphoria and exhilaration.

(b). *Comfort of support without pressures on the skin*—was often reported.

(c). *Sensation of falling*—was rarely experienced and fear and panic responses were infrequent.

(d). *Knowledge of limb position*—the static positions of limbs were known, but moving limbs sometimes caused confusion, overreaching, and an oscillating centre-of-mass.

(e). *Knowledge of body position*—subjects who were not rotating appeared content with their concept of *postural orientation* of themselves rather than the vehicle as a frame of reference.

(f). *Knowledge of rotation*—subjects tended to underestimate their own rates of rotation, and spinning manoeuvres caused disorientation but no dizziness.

(g). *Knowledge of surface location*—knowledge of surface location was poor and knowledge of body-to-surface alignment was almost non-existent when the aircraft cabin was dark.

(h). *Concern over collision*—concern with potential body injury during a surface collision was a dominant apprehension. The unawareness of an approaching surface and the inabilty to rotate oneself and prepare for a landing were reported as major fears.

(i). *Illusions*—the complex acceleration pattern of the manoeuvre induced real and apparent motions of the environment.

(j). *Sense of heaviness after manoeuvre*—the frequent sensation of excessive body weight sometimes lasted hours after a flight of many manoeuvres.

(k). *Decrease of clothing pressures*—often gave the first indication of diminished g.

(l). *Motion sickness*—the majority of naive subjects showed various symptoms of motion sickness which was probably caused by the quick transition from +g to 0g in the aircraft manoeuvre.

The experience of many observers in flight indicates that *orientation* is not a problem during short periods of weightlessness as long as visual and tactual references are available. The body of evidence to date strongly supports postural factors as being the primary ones for perceiving the postural vertical and exerting a very strong effect in the perception of the visual vertical (Loftus 1961). Hammer (1962) suspects a decrement of judgment of the *subjective vertical* in an unstructured (dark) visual field during weightlessness. Although the error of judgment is not large, such a finding would suggest that the zero-g environment offers the experimenter the opportunity to study the mechanisms by which cues from various sensory modalities are integrated in the precept as well as specify the contribution of a specific physical stimulus by systematically reducing its value. The elimination of g may yield new understandings of the complex behaviour of such orientation sensors as the vestibular mechanism.

Pigg (1961) has found an average *visual acuity* decrement equivalent to a 6 per cent increase in visual angle of targets at threshold legibility ; however, for ordinary purposes of vision this is not of practical significance.

Tests of *psychomotor performance* have shown that a person firmly attached to his workplace can carry out many psychomotor tasks with reasonable proficiency and that practice improves performance (Wade 1962). If the problem of inadvertent tumbling can be avoided, it appears that a free-floating man could perform many tasks adequately.

The physiological activity that has received the most attention is the *circulatory system* (Graveline 1960). The greatest risk of circulatory failure may occur upon reentry to a high g field, after the muscles and circulatory system have become adjusted to the changed pressure relationships that are due to zero gravity. Graveline is currently exploring the use of pulsing tourniquets for maintaining proper circulation during weightlessness.

Les mouvements d'un sujet flottant librement en état d'apesanteur sont l'objet de la discussion.

Les techniques d'étude comprennent l'analyse physique des mouvements, la validation en vol de ces analyses et la projection mathématique de l'orbite probable des mouvements. On examine en outre les sensations que font naître ces mouvements.

La liberté de mouvement d'un sujet sans contact avec aucune surface de support fait apparaître de nombreuses exigences à la fois pour la restriction et l'augmentation des mouvements ; des dispositifs tels que main-courante, chaussures à semelles adhésives et moyens mécaniques de déplacement corporel sont nécessaires pour limiter et contrôler ses mouvements.

Les effets de l'apesanteur passagère sur les fonctions sensorielles, psychomotrices et motrices se sont avérés mineurs, mais la perception posturale de la vertical et la réponse du système circulatoire lors du retour à l'état normal de gravité sont considérés comme des problèmes importants.

Die Bewegungen des schwerelosen frei-schwebenden Arbeiters werden besprochen. Die Untersuchungen umfassen physikalische Analysen der Bewegungen, die Bewertung der Analysen und die mathematischen Projektionen wahrscheinlicher orbitaler Bewegungen. Die Sensationen, die durch diese Bewegungen entstehen, werden diskutiert.

Die Bewegungsfreiheit des unbelasteten oberflächen-freien Subjekts macht viele Hilfspunkte notwendig, wie Rettungslienen, adhäsive Fussbekleidung und selbst-steuernde Elemente, um die Bewegungen zu begrenzen und zu steuern. Die Wirkungen vorübergehender Schwerelosigkeit auf sensorische, psychomotorische und motorische Funktionen sind nur geringfügig. Wahrnehmung der vertikalen Stellung und die Reaktion des Kreislaufsystems auf die Wiederkehr der Schwerkraft werden dagegen als wichtige Probleme angesehen.

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