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MON. 9-6-04

The Art of Space Flight Exercise Hardware: Design and Implementation

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The design of space flight exercise hardware depends on experience with crew health maintenance in a microgravity environment, history in development of flight-quality exercise hardware, and a foundation for certifying proper project management and design methodology. Developed over the past 40 years, the expertise in designing exercise countermeasures hardware at the Johnson Space Center stems from these three aspects of design. The medical community has steadily pursued an understanding of physiological changes in humans in a weightless environment and methods of counteracting negative effects on the cardiovascular and musculoskeletal system. The effects of weightlessness extend to the pulmonary and neurovestibular system as well with conditions ranging from motion sickness to loss of bone density. Results have shown losses in water weight and muscle mass in antigravity muscle groups. With the support of university-based research groups and partner space agencies, NASA has identified exercise to be the primary countermeasure for long-duration space flight. The history of exercise hardware began during the Apollo Era and leads directly to the present hardware on the International Space Station. Under the classifications of aerobic and resistive exercise, there is a clear line of development from the early devices to the countermeasures hardware used today. In support of all engineering projects, the engineering directorate has created a structured framework for project management. Engineers have identified standards and "best practices" to promote efficient and elegant design of space exercise hardware. The quality of space exercise hardware depends on how well hardware requirements are justified by exercise performance guidelines and crew health indicators. When considering the microgravity environment of the device, designers must consider performance of hardware separately from the combined human-in-hardware system. Astronauts are the caretakers of the hardware while it is deployed and conduct all sanitization, calibration, and maintenance for the devices. Thus, hardware designs must account for these issues with a goal of minimizing crew time on orbit required to complete these tasks. In the future, humans will venture to Mars and exercise countermeasures will play a critical role in allowing us to continue in our spirit of exploration. NASA will benefit from further experimentation on Earth, through the International Space Station, and with advanced biomechanical models to quantify how each device counteracts specific symptoms of weightlessness. With the continued support of international space agencies and the academic research community, we will usher the next frontier in human space exploration.

I. The Inception of Exercise Countermeasures

THE first experiments with an exercise device as flight hardware occurred on Gemini IV, the second manned mission in the Gemini program (11). Provided medical data from a bioinstrumentation system and post-flight analysis of physical fitness, investigators were unable to observe evidence of a decline in physical fitness. The Apollo program started in 1968 with a plan to accommodate flight exercise hardware. In-flight hardware included a cycle ergometer as well as a rope and pulley device with friction-varying control. Spacecraft issues with weight kept the ergometer off the vehicle and weakened the planned exercise program. Thus, it was during the Apollo Era that crew health signs revealed a pattern of deconditioning, weight loss, decreased muscle mass, and a significant reduction in post-flight physical fitness (11).

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The art of producing space flight exercise hardware demands a strong background in human physiology and general health maintenance paired with engineering excellence in technical skill and project management. Our goal of maintaining crew health remains paramount to the vision of exploring the Earth, Moon, Mars, and beyond. This paper will show the growth of our exercise countermeasures system and the challenges that remain before man can live in Space.

II. Studying the Effects of Long-Duration Space Flight on the Human Body

At the beginning of the NASA's operation, some predicted that humans would not be able to withstand the working environment of space or survive the first manned Mercury launch (14). After more than 40 years of crew health and life sciences experimentation and studies, we are confident that humans can endure long-duration space flight. The challenge now is to determine how to extend the time that humans can live in space while limiting hazardous changes in crew health that result from the weightless environment of space.

A. NASA's Experience in Crew Health and Life Sciences

Throughout the history of the space program, researchers have been gathering information to quantify the effects on the human body from extended stay in a microgravity environment. Initial studies relied on expert opinion and Earth-based experiments to create a baseline of methods for maintaining crew health and physical performance (1). Most of the experimental studies were conducted as part of the Skylab program, Extended Duration Orbiter Medical Project (EDOMP), Shuttle-Mir flights, and the International Space Station (ISS).

1. Skylab Program

The Skylab program was conducted from May of 1973 to February of 1974. Of the four Skylab missions, three were manned for durations of 28, 59, and 84 days (9). This program provided an opportunity for longitudinal studies on crew exercise performance and the ability of exercise to counteract the problems observed during the Apollo missions (11).

Investigators studied muscle strength loss and bone properties in crew members throughout the manned missions of the program. For the study of muscle strength, a number of variables, including body mass, weight, leg volume, force and work were measured to provide information about the average change in leg volume, arm strength, leg strength, and additional measures of exercise performance. For the experiment on bone properties, investigators evaluated bone mineral content and density (9). Results showed that leg volume and muscle isokinetic strength decreased, maintenance of aerobic capacity improved with increasing exercise intensity, and postflight recovery schedules were reduced with increasing exercise intensity (1, 15). Most experimental results verified conditions witnessed by crew members during the Gemini program (16).

After the Skylab program ended, the Space Shuttle was being designed and fabricated, and no missions were flown until 1981. The Spacelab facility was launched in the payload bay of the new Space Shuttle three times from 1983 through 1985. Additionally, the D-1 Spacelab mission dedicated to the German Space Agency (DARA) flew in 1985. During these early years of early Shuttle exploration, no experiments using the Spacelab facility were conducted on humans. With the loss of Challenger in 1986, no further experiments flew until the EDOMP program began.

2. EDOMP

The EDOMP program lasted five years (December 1989 - September 1995) and had the objective of investigating physiological effects of microgravity on skeletal muscle strength, skeletal muscle endurance, aerobic capacity, and orthostatic function (12). Background knowledge at the time included the Skylab experience as well as expert opinion and Earth-based analog studies (1). An additional premise for the program was to look at space flight effects on crew health during missions of less than or equal to 16 days in length. Specified goals included sustaining the pilot's ability to land the vehicle and ensuring the capability of crew members to execute un-aided egress and bail out under standard or emergency conditions (12, 1).

The overall summary of functional performance evaluation experiments presented major recommendations for continued study of crew health and validation of exercise countermeasures. From the first Spacelab missions, opinions had developed that extra-vehicular activities (EVAs) were significant tasks that placed an intense demand on the upper extremities and deserved focused attention for the construction phase of the International Space Station (ISS) (11). EDOMP experiments showed signs of skeletal muscle atrophy, loss of

strength in antigravity muscle groups, and positive conditioning effects from treadmill use. These findings indicated that a specific region existed that had increased sensitivity to microgravity conditions. In the area of aerobic conditioning, studies showed a dependency of suited egress capability on aerobic fitness, higher cardiovascular demand after landing, and a relationship between high intensity workout and lower losses in VO₂ output. Decreased total body protein and non-fat weight were the observable signs of changes in body composition (12, 1). The conclusions as a whole presented more quantifiable indicators relating to the observed effects of space flight that was found during the Skylab program. The test battery used then included magnetic resonance imaging, use of biochemical markers, and muscle-function testing. In the end, recommendations were given for developing a guideline on how soon a countermeasure can be repeated during the time before re-entry, if landing is delayed. Additionally, a request was made for better documentation of post-flight aerobic capacity (12). The investigators considered pre-flight training, in-flight exercise, and post-flight rehabilitation to be an efficient and objective way to evaluate exercise countermeasures.

Throughout the EDOMP program, NASA flew the experiments in many configurations using Spacelab and SPACEHAB facilities. The missions included two Spacelab Life Sciences missions (SLS-1 and SLS-2), a mission (D-2 Spacelab) dedicated to experiments designed by DARA, the German Space Agency; a mission (Spacelab-J) dedicated to NASDA, the Japanese Space Agency; International Microgravity Laboratory (IML) missions 1 and 2; SPACEHAB missions 1, 2, and 3; and the US Microgravity Laboratory missions, USML-1 and USML-2 (9).

3. Shuttle-Mir Missions

The Shuttle-Mir missions, which took place between 1995 and 1998, provided the US space program with many benefits (9). Experiments were conducted on the Russian space station Mir after the Soviet space program had comprised many years of experimentation and experience maintaining the Salyut space station (13). With ISS on the horizon, the Shuttle-Mir missions provided wonderful preparation for the support of long-duration space flight in the US space program. The approach for this period of space exploration was to adopt aspects of the Russian Countermeasures Program, which was based on the past history of Russian expert opinion, experience, and research in crew health maintenance (1). Additionally, the partnership gave the US program more insight into the lessons learned by Russian investigators about crew health factors in long-duration space flights.

From an experiment with the Lower Body Negative Pressure (LBNP) device, investigators learned that using separate sets of hardware and varying experiment protocol compromised their control studies and sample size in experiments. For this reason, conclusive comments could not be made for the experiment on orthostatic intolerance with use of the LBNP device (9). This finding provided positive support for a need to standardize certain aspects of the US and Russian countermeasure programs. Other experiments were focused on control of posture, changes in muscle tissue, monitoring of aerobic capacity with cycle ergometry, calcium metabolism and bone tissue, effects of long-duration space flight on coordination, biomechanics of movement, neurovestibular responses to microgravity, skeletal development in microgravity, and bone mineral dynamics in microgravity (9). The main observations of these experiments were the presence of decreased muscle strength and volume in the back and leg muscles, signs of significant loss in bone mineral density for all crew members with large variability in the type and region of change within individuals, and evidence of altered posture stability after landing (1).

Aside from the missions that docked with or took place on board Mir, two flights in 1996 used the SPACEHAB facility and one flight used the Life and Microgravity Spacelab (LMS). The LMS missions contained two major experiments on muscle relationships. Tests considered electromyographic activity and hormonal function versus results for muscle atrophy and performance. Another study on the LMS mission, involved a follow-up experiment researching bone based on studies from SLS-1 and SLS-2 (9). The next year (1997), a mission used the Microgravity Science Laboratory in the Spacelab facility but did not include studies on exercise performance. The last Spacelab mission flew in 1998 with the Neurolab group of experiments. In the same year, STS-95 flew with the Hon. John Glenn, and NASA conducted important research on crew health under a partnership with the National Institute on Aging of the National Institutes of Health (9).

4. International Space Station

The ISS program is a monument to the history of space exploration. With the partnership of over 15 countries, the ISS will facilitate experimentation in many fields of study in a microgravity environment. The construction of the ISS began in November of 1998. In adherence to the vision of manned space flight, the ISS has supported experiments to further our understanding of how humans can endure long-duration space flight.

The first mission of Increment 2, in 2001, included experiments on the changes in spinal cord excitation under reduced gravity and on assessment of bone loss in the axial skeleton. Since that flight, other missions have accommodated experiments on radiation exposure, pulmonary function, risk of kidney stone development, presence of a natural cardiovascular reflex to counteract light-headedness upon return to Earth's gravity, changes in skeletal muscle, factors of dysfunctional locomotion upon return to Earth's gravity, and foot ground reaction forces during normal activities in space. Although results have not been published, the objectives for the bone and muscle studies are to develop a method of determining the allowable frequency of long-duration space flight for an astronaut, and to develop a model to anticipate the time needed for proper recovery after a mission (9).

The Space Station program had completed 20 flights supporting Station assembly and progress before the loss of STS-107 and its crew. When the Shuttle program returns to flight in 2005, the experiments can be completed.

B. Today's Requirements for Exercise Countermeasures

In the environment of weightlessness, our bodies begin to take on a series of changes. Two noticeable changes are loss of muscle mass, bone density, and water weight. At the heart of these physiological changes, it is the cardiovascular system, which exacerbates the cycle of decay in crew health and physical fitness. While it is possible to force feed astronauts, the balance of fluid intake and output will lead to an increase of fat weight due to inactivity in a weightless environment. However, exercising provides the opportunity of strengthening muscle and bone while increasing cardiovascular capacity. As exercising increases cardiovascular capacity, the decrease in bodily fluids bears less impact on the cardiovascular capacity. Performing exercises represents a more efficient method of administering the gravitational effects of Earth on the human body than forcing fluid intake. Thus, the key countermeasure for preserving and protecting crew health will be exercise (1).

The goals for exercise countermeasures are to minimize physiological alterations, guarantee effective in-flight performance, provide functional return to Earth, and promote an optimal rate of post-flight recovery. Achieving these goals should ensure that crew health is maintained as close as possible to Earth-based levels and that no career-limiting health concerns arise for crew members (1, 2, 4, 5). The Countermeasures System (CMS) is one of three components of the Crew Health Care System (CHeCS), which includes the Environmental Health System and Health Maintenance System (5). Under the current CHeCS program, CMS hardware comprises all exercise devices and supporting hardware to quantify exercise performance. Supporting devices provide the capability to monitor heart rate and pulse, blood pressure, electrocardiogram, data collection, data storage, and data transmission.

The exercise devices must provide aerobic exercise and resistive exercise as well as support EVA pre-breathe activities. The aerobic exercise workload is 60 minutes for 7 days a week whereas the resistive exercise workload is 90 minutes for 6 days a week (2). Table 1 shows the breakdown of requirements for exercise hardware that comes from the exercise performance results of past experiments and exercise prescriptions.

Table 1. The Current Exercise Prescription for Flight Crewmembers

Requirement	Frequency	Comment
Cycling	3 days/wk	Alternate daily for entire week
Running	4 days/wk	
Resistive Exercise	6 days/wk	Perform on all but one days of the week

III. Exercise Hardware Profiles Throughout the History of Space Exploration

Looking at the history and progression of space flight exercise hardware can demonstrate key challenges in design. Through the years, major development in exercise countermeasures has taken place at Marshall Space Flight Center, Ames Research Center, Johnson Space Center, in other international space agencies and at research institutions throughout the world. Major factors in the design of exercise hardware have been human factors, ergonomics, mounting and size requirements, and environmental limitations on the hardware because of its deployed location. Ultimately, the best contributions to the design process come from the first-hand experience of astronauts.

A. Pre-Skylab

Before the Skylab program began, NASA completed the Mercury, Gemini, and Apollo programs including an Apollo-Soyuz mission. The Mercury program had no exercise devices, exercise prescription, or crew space to perform any worthwhile exercises within the capsule (11). The Gemini program instituted a bungee exerciser for the Gemini IV mission and implemented isometric exercises during the Gemini VII mission. The bungee exerciser was the first in-flight exerciser used in our space program (11, 1). Finally, the Apollo program had a rope-and-pulley, variable-resistance device for exercising (1) and the first design of a cycle ergometer was dropped from the program because of weight constraints (11).

B. Skylab

Skylab II was the first manned Skylab mission. The Skylab II crew depended on a cycle ergometer for exercise (14). During the mission, it took 10 days for the crew to learn how to ride the cycle ergometer and they eventually discarded the shoulder harness accessory designed for the device (11). The Skylab III crew relied on the MKI isokinetic rope-pull device, also known as the commercially available Mini Gym designed by Glen Henson (11, 15), and the MKII handle-and-spring assembly exerciser, in addition to the cycle ergometer. The cycle ergometer received good evaluations thanks to the Skylab II commander's use of the device for upper-body strengthening. The Skylab IV crew was the first to use the Teflon Treadmill, developed by NASA astronaut Dr. William Thornton, along with all previously existing exercise devices during the program (1, 11). This treadmill system had a slippery Teflon running surface, which the crew members would run on while wearing only socks on their feet.

C. Space Shuttle

A passive treadmill developed by Dr. Thornton was first flown on STS-3 (11). Both the pilot and commander used the treadmill extensively in support of their duties to control shuttle landings. The early treadmill produced high levels of noise because of the design of its running surface. The belt was a series of aluminum plates with rollers on the ends to follow a guide track for passive functionality. Observations were made that the acceleration of the treadmill structure could transmit loads to the shuttle structure and disrupt surrounding zero-g experiments. Beginning with this version of the treadmill in the Spacelab facility on the Shuttle, an EDO Treadmill was developed for the EDOMP program. This treadmill was radically different from the Shuttle Treadmill in comfort, noise output, and workload quantifying capabilities (12) and its initial launch was on STS-64 (9). The belt design for the EDO Treadmill incorporated a fabric belt over plastic slats that rolled on two drum wheels and reduced noise levels significantly (12). The system was passive with the option of using orbiter power for the control panel instrumentation. The EDO treadmill is the basis of treadmill development for the ISS.

As a form of resistive exercise in the EDOMP suite of exercise hardware, the EDO Rower flew in two generations of design that utilized the MKI and MKII devices featured in the Skylab program (12, 7). The first generation EDO Rower used the MKI device and served the project from STS-42 to STS-56. The second-generation EDO Rower flew for the first time on STS-64 and had the major improvement of implementing workload quantification on the MKII platform. The rower only needed foot restraints. Using a conventional rowing form, it did not need a seat or any further restraints (12).

A cycle ergometer developed after the time of Skylab joined the set of exercise devices in EDOMP. In preparation for the D-2 Spacelab mission, the European Space Agency (ESA) issued a contract for development of a cycle ergometer for the Anthrorack experiment. The ergometer was designed for computerized control with a steady workload for any pedaling frequency. Having seen the functionality of the cycle ergometer, NASA-Johnson Space Center (JSC) issued a contract to have ergometers developed for the EDOMP program. The mounting frame, accessories and pedals were developed at JSC. The Life Sciences Laboratory Equipment II was the ergometer on Spacelab mission SLS-2 and flew up in the same year as the D-2 Spacelab mission. However, the first cycle ergometer of this design flew on STS-42 in 1992. The final design had a minimal seat back, based on KC-135 testing, that was comfortable in zero-g without a full seat. The other observation was that handlebars were not preferred as they caused arm fatigue and did not contribute to comfort or support. One of the most significant design challenges involved the cycle ergometer frame because of constraints on the deployed location and delivery requirements in the payload (12). The loading module for the current cycle ergometer is still the same as the one developed by the contract issued in 1985 by ESA.

Vibration isolation was an issue for the EDOMP program, so the vibration isolation system (VIS) for the ergometer (EVIS) was developed to address this issue. EVIS used motors that required too much power, so they were not used for any further study. The lessons of EVIS were applied to the passive cycle isolation system, or

PCIS. PCIS seemed to work as expected, but expectations increased and called for better stabilization. The final effort was the Inertial VIS, IVIS, which was designed to work with PCIS (12).

D. Shuttle-Mir

This program brought together the strengths of two programs by involving the use of US and Russian countermeasures hardware. The featured hardware included a cycle ergometer, velo ergometer, Shuttle treadmill, Russian treadmill, penguin suit, and Russian expanders (1).

Exercise countermeasure protocol for the Russian program used the Chibis suit and penguin suit (13). The Chibis suit was designed as a lower body negative pressure suit and the Penguin suit had elastic elements woven into it so that it constantly applies resistance to the individual wearing the suit. Other devices listed under Russian countermeasures hardware include the bracelet device, carcass device, and Tonus-3, the electrostimulator (6).

The Russian program also had a bicycle ergometer called VB-3 or the velo ergometer. Again, NASA developed additional cycle ergometers and installed one unit in the Spektr module of Mir.

The force loader, also known as HC-1, was a resistive exercise device designed for upper body resistive exercise. On the part of US Hardware, there was no resistive exercise device available. The EDO Rower was the last resistive exercise device in use.

The Russian treadmill named BD-1 is designed to function both passively and motorized. Conditions to the design of BD-1 forced the device to service as a passive exerciser. Other versions of the Russian treadmill design are UKTF and UKTF-2. The Shuttle treadmill was the same as the one in use during EDOMP.

E. International Space Station

With the ISS, the US space program begins a new journey that carries on what the Mir and Salyut started. The ISS contains the CEVIS, velo ergometer, TVIS, penguin suit, iRED, and Russian expanders (1).

CEVIS is a cycle ergometer with vibration isolation system and touch screen control panel interface. Further work on noise reduction inspired an additional noise reduction jacket for the loading module. Hardware problems for CEVIS have been rare, and it is the best piece of hardware from the standpoint of availability and maintenance (3).

TVIS is the treadmill with vibration isolation and stabilization. The VIS for this treadmill utilizes the concepts developed in the design of the EVIS, PCIS, and IVIS during the EDOMP program on the Space Shuttle. The ISS treadmill has not been able to maintain consistent operation under nominal configuration due to restrictions on its motorized mode and use of the subject loading device (3). In addition, a redesign of the Subject Loading Device is needed to extend the operational life of the device (3). The main desire at this point is to secure reliability and availability of the TVIS while increasing its capability in loading, belt speed, and harness design for comfort (3). An investigation has been done to consider the possibility of providing a contingency exercise surface, similar to the earlier Teflon Treadmill from Skylab, to accommodate treadmill use (17).

The current interim resistive exercise device is called the iRED. This device has imposed many limitations on crew exercise because it has inadequate loading ranges for major exercises and a range of motion reduced by hardware constraints. In addition, the device requires an intensive maintenance schedule for replacement of the resistance modules. One device that is under development for the future is a completely new concept called the advanced resistive exercise device (ARED). During the design and development period for the ARED, a contingency measure has been implemented to reduce excessive costs of maintenance for the iRED. The contingency device is called the Schwinn resistive exercise device (SchRED) and improves on the iRED with a new design of the resistance modules (3, 8). This device has not addressed the lack of vibration isolation on the iRED; thus, development of the ARED is still necessary.

Russian countermeasures hardware complements the US hardware in many ways. The velo ergometer is similar to CEVIS. The penguin suit is the same as the one used in the Shuttle-Mir program, and the Russian expanders are simply a bungee cord system that accommodates isometric exercises (6). Steps are in place to incorporate contingency measures that will allow usage of Russian hardware such as the Russian treadmill. This will provide redundancy in the countermeasures system and protect against losing the capability to fulfill exercise prescription requirements.

With the current CHeCS System of CMS Hardware, the full list of hardware includes a blood pressure/electrocardiogram device, the MEC, EVA training equipment, and a heart watch with heart rate monitor

(2). The MEC is a computer dedicated to data storage and transmission for medical experiments. EVA training equipment includes bungee cords, handgrip devices, and other tools to strengthen the hands and forearms.

Overall, CMS hardware needs to provide more exercise performance data and storage capabilities for easy data transfer (4, 8). Future improvements on hardware will reach higher levels of precision if crew health indicators are more definitively correlated with exercise performance.

IV. The Design and Development of Exercise Countermeasures at NASA

The challenge to design exercise devices as flight hardware exists in the same way as the challenge to build all other hardware for space. The engineering directorate follows a specific plan for project management that promotes reliability and imparts a structured methodology to the design process. This process incorporates eight phases during the design life cycle that takes a project from its initial suggestion to the final deployment and maintenance as space hardware (10). All exercise hardware and health-monitoring systems currently in development have been developed using the process described below.

A. Feasibility Assessment

The first phase of the development life cycle begins with a request for government furnished equipment (GFE) submitted to the engineering directorate by a sponsoring program. The Engineering Project Management Office assembles a feasibility assessment team to consider the technical, resource, and schedule feasibility for the request as well as the safety, risk and quality demands of the GFE description. To ensure project success, it is important for the feasibility assessment team to test the demands of the proposal through early conceptual design and prototyping to prove that the demands are supported by engineering fundamentals. The team provides its assessment in a report to engineering management for approval and the management office provides a project code for the proposal. An appointed project manager will develop a project file to document the design process until its completion. The project managers for exercise countermeasures rely on technical expertise in the Space and Life Sciences Directorate to evaluate the feasibility of requirements where exercise performance metrics must be translated into hardware performance metrics. This is necessary to create a connection between human health and device functionality.

B. Project Definition and Approval

For any new project, the project manager must develop documentation for formal agreements between organizations, centers, and divisions that will jointly participate in or support the design process. In the agreement, the goal is to establish a consensus on issues regarding the project resources, facilities, budget, and schedule. This document is updated throughout all phases of the design life cycle to capture the agreement between the proposal party and engineering as well as all groups supporting the development of hardware. In addition, the agreement aims to define the project scope by specifying top-level requirements that are defined in full during the next phase of development. The project manager must also create documents to explain the management methodology they will use to manage the design process. In certain cases, less complex hardware can be developed by combining phases of the design life cycle or by using alternative documentation procedures. These types of decisions must be documented and approved in the proposed methodology. On a more concrete level, a work breakdown structure describes the steps in each aspect of hardware development for the entire project plan, to map all components of design to resources, facilities, budget, and schedule. The mapping connects real actions to proposed methodology. At this stage of the life cycle, the partner agreements document establishes cost estimates from the preliminary phase to the next phase, requirements definition. Before moving on to the next phase, all parties should ensure that the design intent, scope, and direction are understood and accepted by everyone included in the agreement documents.

C. Requirements Definition

With an approved methodology, plan of action, and agreement documentation, the sponsoring program must provide a financial commitment to the project to continue with the requirements definition phase. This is the critical phase where all design requirements are established between the project team, proposal party, and supporting organizations. The project team documents all design requirements and tests that are necessary for future validation, verification, and approval of the GFE. Exercise flight hardware must currently be designed to integrate into the existing structure of the Space Shuttle or the ISS. The preliminary interfacing requirements are listed in their own document. At this stage quality assurance, safety, and the Mission Operations Directorate assist to clarify safety

requirements and interface issues for the specified location of the GFE. Expertise, from the Space and Life Sciences Directorate, in human factors and ergonomics is crucial to the design of exercise hardware. In addition to issues of maintenance and calibration, exercise hardware is required to include instrumentation for monitoring crew health. The large size of standard exercise devices presents a unique challenge when designing according to the requirements for emergency egress on the ISS. In addition, the sensitivity of experiments on the ISS presents an additional challenge to prevent the transmission of vibrations from the exercise hardware to the ISS structure. Furthermore, the greatest contribution to engineering design requirements comes from past crew members who can articulate the nature of exercise in a microgravity environment. Now the agreements documents are completed to show a cost estimation through completion of the project.

D. Preliminary Design

This phase begins after the project requirements and preliminary interface requirements receive approval in a system requirements review by the sponsoring program, engineering, safety, mission operations, astronauts, and supporting organizations. Preliminary design is considered to include the first ten percent of design progress. Initial decisions are made on items to be purchased or designed and critical components of proposed hardware concepts are prototyped. At this stage of design, astronauts are often invited to evaluate exercise device prototypes and to provide feedback by describing their initial reaction to the design. The project manager composes a risk assessment report within a safety data package for review by the safety review board. At the same time, the design team begins to create engineering drawings and creates the plan for implementing validation and verification testing. In preparation for a preliminary design review (PDR), the project manager updates the agreements documentation and interface requirements, and combines the team responses to issues raised in the safety review board with all design drawings and prototype results for presentation in the PDR. The main design decisions to make early on deal with maintenance needs of heavily cycled components. For example, for a device that requires maintenance on a monthly basis, crew time on orbit will be a serious consideration, as well as excessive costs if spare components must be supplied during the same time frame via the shuttle payload.

E. Detailed Design

The detailed design phase includes the remaining design development for the GFE. Participants in the PDR can submit concerns and feedback to the project team as an action item for review at the critical design review (CDR). The CDR is the equivalent of the PDR when the detailed design phase nears completion. In this phase, all engineering drawings, interface requirements, and safety reviews are completed with the final design, and validation test plans are fulfilled according to the project requirements defined earlier. Moreover, the earlier prototype is developed into a full mock-up for presentation at the CDR. The project manager continues to update the agreements document and secures a final agreement with the proposal party on cost before entering the CDR.

Overall, design issues present various challenges because the crew members are responsible for all maintenance of the exercise hardware. Unlike members of a fitness club, the crew must clean and service the exercise machines they use. Therefore, the "grunge factor" of crew perspiration during exercise consumes crew time for sanitization of the exercise hardware. Also, hardware designed for on-orbit maintenance will be more highly valued as crew time needed for replacement of spare components or calibration procedures decreases.

F. Flight Production and Certification

Completion of the CDR provides a baseline for the hardware fabrication process. At this stage, the project team begins to fabricate flight-quality units for qualification and acceptance. The process involves formation of an Acceptance Data Package (ADP), which combines all documentation for testing and validation. For the Qualification Unit, engineers perform specified tests to show that the hardware performs according to the specifications called for by project requirements. The second Qualification Unit undergoes certification as the specific assembly of hardware to be deployed for use in space, and the documentation for this unit builds upon the ADP to form a Certification Data Package. Along with the responsibility for testing hardware, the project team is charged with fabrication of the hardware, preparation of software, and the provision of ground support hardware for testing. The System Acceptance Review (SAR) surveys all testing and validation documentation and covers documentation on plans for sustaining engineering, maintenance, user documentation for the hardware, and a final clearance by the safety review board. The SAR presentation may include a plan for final testing before launch at the launch site. For exercise hardware, testing and validation carries a long project schedule to accommodate component and system lifecycle testing as well as man-in-loop testing. Although it is possible to certify hardware to a certain performance level, it is much more difficult to certify that a device can support human performance at a specified

level. The human aspect of exercise hardware design introduces variables that currently can be verified only by operating the hardware with a human in the test setup.

G. Deployment

The deployment phase is the point where GFE is approved for flight and is officially assigned a mission number for deployment or implementation. A target flight for delivery is commonly specified in the initial project description. Before delivery, the hardware undergoes a pre-flight test. At this stage, the project manager must complete paperwork to give the sponsoring program ownership of their hardware, to approve hardware for shipment, and to support a document for certification of flight readiness (CoFR). The CoFR is a readiness endorsement to ensure that all pending issues are finalized and approved by the appropriate parties. After delivery of the GFE, the final reviews take place before the flight readiness review is performed. The final reviews include the crew equipment interface test (CEIT), bench review, and various other reviews specified by the project team. The CEIT occurs only for the first use of the hardware for the vehicle it is used on. If the hardware is an item that the crew will use operationally as an interface, then the equipment must pass a bench review.

H. Operations

The final phase of the design life cycle emphasizes the mission planning support for all hardware. This phase places the engineering project team in a supporting role to perform any needed engineering analysis on the hardware or to perform sustaining engineering and maintenance tasks. The agreements document finalized at the CDR is now updated or supplemented by a new document to specify sustaining engineering tasks. While the project team provides engineering analysis, the project manager compiles a lessons learned report based on the experiences of the project team. At the end of a mission, the hardware receives an end of mission review (EMR) and is handled according to its specifications for stowage and maintenance or disposal. The EMR marks the end of the eighth and final phase of the design life cycle.

V. Conclusion

After more than 40 years of experience, we are still challenged by the problem of how to ensure crew health during long-duration space flight. The limitations to our scientific abilities originate in the inherent small population of astronauts that can be tested; the great variations in their responsibilities, from EVA tasks to conducting research; differences in mission durations; and space flight constraints on power, launch weight, crew and training time, and stowage space (1, 2). In addition, it has been a challenge to assess the efficacy of CMS hardware items independently of each another (2). Exercise countermeasures thus far have not maintained crew health at the level desired by the medical community at JSC. Advisory committees have concluded generally that heavy resistive exercise is needed for exercise over the entire range of motion, which focuses on at-risk muscle groups of the hip and lower back, as well as for EVA and egress procedures (1, 2, 5).

The CMS collection of exercise hardware operates under the classification of nominal, contingency, or flight rule. The three main exercise devices, iRED, TVIS, and CEVIS, have special contributions or specialties with respect to each other. If a device is unavailable for use, contingency or flight rule configurations are put into place and there will be a 60-day window for abortion of the mission. In the event that two devices are non-operational under nominal configuration, the window for mission abort is 30 days (8). This shows that exercise countermeasures are so important that loss of one or two of them could end a mission before it is completed. Engineering support must do everything possible to ensure that the hardware is reliable and requires moderate to low levels of maintenance.

As these exercise requirements carry over to longer periods in space, maintenance and resupply become critical topics. In the days when humans explore Mars, program logistics will not be available to send resupplies of spare mechanisms and force modules at the frequency that is currently in practice. The engineering design will have to accommodate maintenance to be done solely by the crew. At the same time, exercise hardware can only improve in reliability if the specifications and requirements are reduced to a more critical set. As the medical community identifies the critical factors in maintaining crew health, the hardware requirements will be reduced to performance metrics for exercising a subset of muscles, rather than giving a total body workout as required today. Although the treadmill and cycle ergometer may continue to undergo redesign for easier maintenance and improved performance, the resistive exercise device may benefit from a more focused set of requirements that specifies a simplified device or one that will break down to a more compact, modular design that can accommodate multiple exercises using multiple configurations. This shift in design may be possible as the medical community continues to quantify critical

biological and physiological conditions for proper crew health (8) and correlate health conditions with performance metrics for exercises. The CMS hardware concepts of the future could shift towards a smaller profile, exercise device with functionality specified for muscle sub-groups, and maintainability solely by the crew. With more compact designs, the hardware will depend on smaller components that can ease the space limitations for storing spares on an extraterrestrial base when exercise hardware maintenance is needed. Alternatively, there may be advantages in simply designing two types of exercise hardware optimized for low earth orbit or extended space exploration.

The presence of humans in space depends on our ability to maintain crew health for extended stays beyond low Earth orbit. To continue the journey, we need to continue the collaboration by engineering, space and life sciences, and academia. Potential tools that can help with the optimization of CMS hardware depend on the partnership of all parties in support of developing an ISS test bed, additional ground-based testing, and biomechanical models for the assessment of equipment effectiveness on maintenance of crew health.

Acknowledgments

The author thanks CMS Summit Participants, Dr. Don Hagan, Mrs. Jackie Reeves, Mr. Tim Pelischek, Mr. Edgar Castro, Mr. Scott Swan, Mr. Jasen Raboin, Mr. Jeff Bye, Mr. Joe Trevathan, Mr. Mike Rapley, Ms. Janine Bolton and the STI Bioastronautics Library

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