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MITIGATING CREW HEALTH DEGRADATION DURING LONG-TERM EXPOSURE TO MICROGRAVITY THROUGH COUNTERMEASURE SYSTEM IMPLEMENTATION

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ABSTRACT

Experience with the International Space Station (ISS) program demonstrates the degree to which engineering design and operational solutions must protect crewmembers from health risks due to long-term exposure to the microgravity environment. Risks to safety and health due to degradation in the microgravity environment include crew inability to complete emergency or nominal activities, increased risk of injury, and inability to complete safe return to the ground due to reduced strength or embrittled bones. These risks without controls slowly increase in probability for the length of the mission and become more significant for increasing mission durations. Countermeasures to microgravity include hardware systems that place a crewmember's body under elevated stress to produce an effect similar to daily exposure to gravity. The ISS countermeasure system is predominately composed of customized exercise machines. Historical treatment of microgravity countermeasure systems as medical research experiments unintentionally reduced the foreseen importance and therefore the capability of the systems to function in a long-term operational role. Long-term hazardous effects and steadily increasing operational risks due to non-functional countermeasure equipment require a more rigorous design approach and incorporation of redundancy into seemingly non-mission-critical hardware systems. Variations in the rate of health degradation and responsiveness to countermeasures among the crew population drastically increase the challenge for design requirements development and verification of the appropriate risk control strategy. The long-term nature of the hazards and severe limits on logistical re-supply mass, volume and frequency complicates assessment of hardware availability and verification of an adequate maintenance and sparring plan. Design achievement of medically defined performance requirements by microgravity countermeasure systems and incorporation of adequate failure tolerance significantly reduces

these risks. Future implementation of on-site monitoring hardware for critical health parameters such as bone mineral density would allow greater responsiveness, efficiency, and optimized design of the countermeasures system.

INTRODUCTION

Human beings are adapted to live and work in the 1-g environment of Earth. Once that biological system is placed in the near-zero-gravity environment of low Earth orbit (LEO), it reacts to the changing stimuli in ways that are deleterious both to continued function on-orbit, and especially to return to normal life back on Earth's surface. As expected, some of the most serious effects on the body involve those systems involved in resisting the pull of gravity including the skeletal system and skeletal muscle groups involved in posture and locomotion.

Effective countermeasures against the effects of microgravity on human beings must be developed if we are to continue to safely complete long-term missions in Space or other worlds with reduced gravity. NASA research of the effects on the human body of long-term living in Space dates back to the Skylab missions of the 1970s, when U.S. astronauts first lived in LEO for up to 84 days. As medical ethics require, NASA has always provided crewmembers with the best countermeasures available at the time, so little data is existent on the wholly unmitigated effects of microgravity on humans. However, the mitigated effects demonstrate the critical nature of the risk:

- Skeletal muscle strength declines by as much as 30% in 3 months [1-3].
- Aerobic capacity decreases by as much as 30% in 30 days [4-5].
- Bone mineral density decreases by as much as 2.5% per month [6].

Countermeasure system concepts currently employed on board the ISS include a treadmill, a cycle ergometer, and a resistive exercise device. Each of these modes is employed to maximize the strengths and usefulness of all in counteracting the effects of microgravity on the body.

Numerous other effects on the body as a result of living in space could negatively affect crewmember performance. Some of these effects include increased radiation exposure, decreased immune response, cardiac arrhythmias, and decreased thermal regulation [7]. Also, locomotor and neurovestibular de-conditioning impacts crewmember safety upon return to Earth. This paper focuses only on the risk of three principal effects indicated above known to result specifically from lack of gravitational stimuli and impact a person's ability to function in space and on return to Earth.

RISK ASSESSMENT

Severity

The available data suggest that without countermeasures, any person placed in a microgravity environment long term will experience degradation in functional capability and health. The seriousness or severity of the risk must be assessed both for continued operations in microgravity (nominal and emergency) and for tasks and activities required during and after return to the Earth. Additionally, there is a potential for chronic health effects following long after the original space flight. Each of the three principal effects examined in this paper to bone, muscle and the cardiovascular system are assessed individually.

Decreased bone mineral density (BMD) results in increased risk of bone fracture, increased risk of renal stones, risk of permanent bone loss, and potentially increased risk of future development of osteoporosis. Bone loss tends to be greatest in the lower body since that part of the human structure experiences the most significant reduction in load due to loss of gravity. See Figure 1 below.

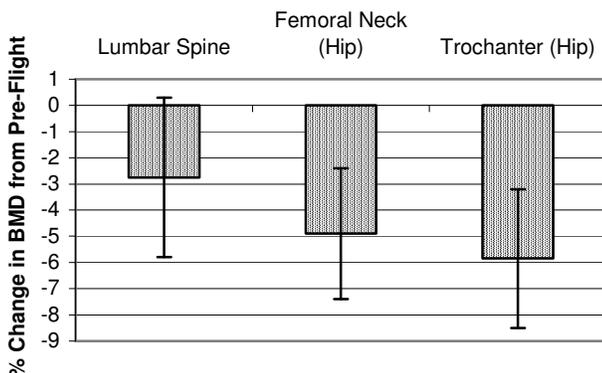


Figure 1: Percent Change in Bone Mineral Density (BMD) for Three Regions in NASA Mir Astronauts (n=7) [4]

Risk of bone fracture during nominal activities on-board the ISS is very low due to the lack of severe loading on the

body, which causes the decreased bone mineral density in the first place. However, the loads experienced by the body during an emergency such as module isolation in the event of a leak or evacuation of the ISS due to a crew medical problem are not as benign or easily predictable. The de-orbit and landing of spacecraft also present a case where skeletal loads would be higher than normal. Shuttle landing profiles include sustained accelerations of up to 3 gs [7]. The landing profile of the Soyuz spacecraft can include sustained accelerations of up to 4.3 gs and shock loads as high as 40 gs [8]. A 2%-4% loss of bone mineral density may not result in a significant increase in these risks, but longer missions such as extended ISS missions or Mars exploration could carry substantial risk in this category if the degradation rate is not slowed or halted. These injuries could temporarily disable a crewmember or result in death when combined with another emergency or failure condition.

The increased risk of renal stones results from secreted calcium from bones increasing the concentration in the blood stream. This risk is somewhat controlled by decreased dietary calcium and medications [9], but reduced or halted bone mineral loss would eliminate this concern as well. Renal stones occurring during a mission could force an immediate return to Earth for treatment, as well as temporarily disable the crewmember involved.

Permanent bone loss and the increased risk of osteoporosis impact the long-term health of the crewmember. While little long term data exists on a person's increased likelihood of future osteoporosis, the similarity in characteristics between the bone loss in microgravity and during osteoporosis suggests a potential relation [10]. A portion of the bone loss that occurs during long-term space travel could be permanent, and the remaining bone loss, requires up to 3 to 4 times the mission duration to recover [9]. For a crewmember in the most susceptible category, a BMD loss of 12% could occur over the course of a 6-month mission; most would recover in 2 years, but some loss from pre-flight would remain. Beyond potential disqualification from future spaceflight, this loss could significantly impact the future life of a person in a high risk group for osteoporosis.

Decreased muscle mass decreases a person's strength and endurance. This decline results in the person not being capable of performing tasks one could previously perform. Although crewmembers are required to have capabilities at the beginning of a mission above the minimums necessary to complete the required tasks, it is possible that the decrements in capability could eventually reach the point of not being able to perform certain mission critical tasks.

Among the most strenuous physical tasks are Extravehicular Activities or EVAs. Since, EVAs are required at certain times to maintain the ISS, they can be considered essential for astronaut capability throughout the mission. In ISS EVAs, only a person's upper body is significantly involved in mobility and performing tasks. EVAs become more difficult when considering planetary exploration. In the situation of a planetary EVA on the surface of Mars or the Moon a

crewmember's lower body will be taxed with supporting the mass of the person and the suit during walking, kneeling, standing, and other activities.

Crew tasks during re-entry when the accelerations apply additional load to the body beyond even what is experienced on the surface of Earth can induce fatigue in crewmembers acclimatized to microgravity conditions. Also, response to an emergency such as the previously mentioned module isolation or medical issue can require strength near the levels typical of activities on the ground.

As seen in Figure 2 below, the decline in lower body muscle strength is significant for long duration missions. Again, the long-term data depicts the physiological response including some countermeasures.

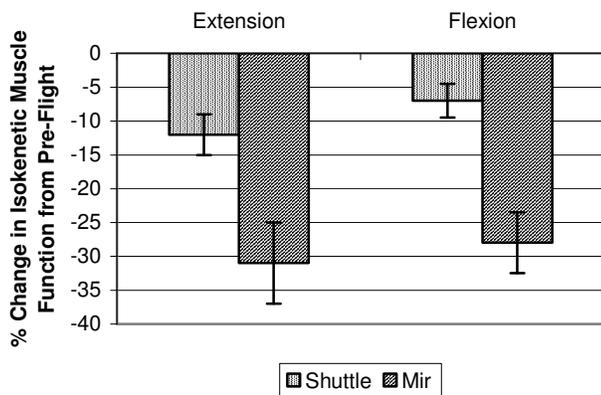


Figure 2: Percent Change in Isokinetic Muscle Function Tests from Pre-Flight for Knee Extension and Flexion (Shuttle {short duration}, n=17; Mir {long duration}, n=5) [1-3]

Aerobic and anaerobic capacity decreases by up to 30% in the first 30 days and then reaches a plateau [5]. From the earliest point in investigation of countermeasures, this effect has proven to be the easiest from which to recover. Crewmembers must retain aerobic capacity in order to complete EVAs and maintain effectiveness during decent, especially important for pilots. Responding to emergencies also requires a certain level of aerobic capacity, probably in line with that of EVAs and decent activities. Early fatigue and greater use of oxygen occur in crewmembers who do not have adequate aerobic capacity.

Crewmembers also experience a drop in aerobic capacity upon return to Earth. A person who has regained his or her pre-flight capacity by the end of the mission will experience a decrease following return. This leads to the conclusion that someone who could not maintain an adequate level or only a marginally adequate level during the mission could experience a greater decline after return to the ground. For someone taking part in a contingency landing scenario by Soyuz or another craft not in an area of rapid medical response, this hindrance could be a serious handicap.

The early fatigue caused by inadequate aerobic capacity can result in serious complications compromising safety of the crew. An inability to perform medical emergency response procedures in a timely fashion increases the risk to other crewmembers by eliminating the last line of defense.

As shown in Figure 3, aerobic capacity declines significantly at the beginning of a mission, even in the presence of the current countermeasures. The decline levels off, and is recovered by the end of the mission with appropriate countermeasure utilization.

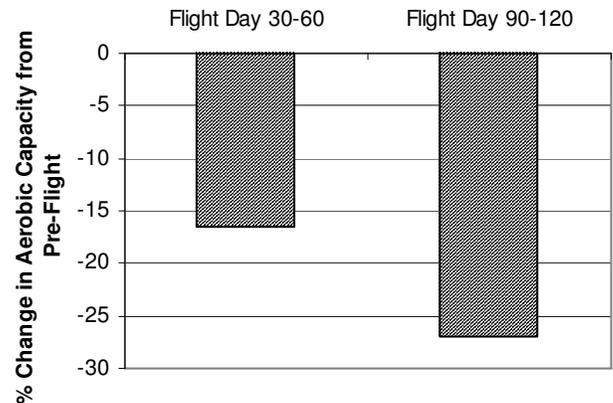


Figure 3: Decline in Crewmember Aerobic Capacity during Mir Mission (n=1) [4]

All crewmembers experience these effects to some degree. Significant variability occurs between individual crewmembers and also between specific sites, regarding muscle and bone, on the same individual [11]. Given that the effects outlined above all occurred in the presence of some countermeasures, it seems certain that these effects would eventually overcome all crewmembers to this degree or greater given enough time. Currently ISS missions last approximately 6-months, but future missions could be longer, and other destinations beyond LEO would almost certainly involve greater time periods. Some limited Russian experience with longer missions, suggests that with countermeasures these effects do not worsen from those presented here [12].

Genetic factors as yet undiscovered are thought to affect both a crewmember's response to the removal of gravitational stimuli, and their response to exercise countermeasures. No currently available method accurately predicts a person's likely response to the microgravity environment. This may be achievable in the future with more data and a greater sample size.

It would not be without reason then, to suggest that all crewmembers given a mission duration of 6-months without countermeasures would experience several functional impairments commensurate with a hazardous condition, and some even with the countermeasures available to date would experience a significant functional impairment in at least one area of concern. This points to the need for continuing

development in the capability or functional envelope of the countermeasures system.

Risk Control or Mitigation Requirements

These effects if evaluated on the ground for a worker, would meet the definition of an occupational illness, which under NASA safety guidelines is called a “critical hazard” and must be protected against with a 1-fault-tolerant or equivalent control approach [13]. Since sub-systems within the larger countermeasures system are directed specifically at a sub-set of microgravity effects, the fault tolerance of the system, is most appropriately analyzed on a function (or target) by function basis. As determined by this analysis, each identified function (e.g., mitigating bone loss) should have redundant success paths. As mentioned previously, NASA does permit an approach without redundancy, if the reliability of that approach would be comparable to systems with redundancy.

The limited nature of the data considering the small sample size, high variability between individual crewmembers, and limited success to date in mitigating some effects means that it is not currently possible to determine a minimum exercise protocol necessary to protect a person from these functional decrements. Without a minimum protocol, capabilities of the countermeasure system must be maximized to ensure the risks are mitigated to the greatest possible extent. This statement concurs with the medical ethics principle, which states that decrements should be as low as reasonably achievable. Until, the determination of the minimum countermeasures protocol can be completed, the countermeasures must be assessed against the presumed overall enveloping requirements for the entire population.

In recognition of the importance of the countermeasures system on-board the ISS, NASA has also implemented requirements governing the maintenance and recovery activities should any countermeasures sub-system fail. Currently, those requirements state that if the entire countermeasures system were to fail, all efforts would be made to restore at least one sub-system within 5 days [14]. In the event of a single failure, capability must be restored within 30 days, according to the requirement. These requirements, while directed at flight control team priorities, imply requirements for adequate supply of hardware components necessary to affect repairs.

In addition to the requirements for countermeasures function during a mission to maintain crewmember effectiveness, NASA also has responsibility to maintain a crewmember’s health to permit a speedy recovery. The flight surgeon, or chief medical officer, has a responsibility to rehabilitate a crewmember following a mission to full flight status within 45 days [5]. So, losses during the mission must be kept to a minimum to permit compliance with this requirement.

COUNTERMEASURES SYSTEM

The concept of microgravity countermeasures is to replace the effects of 1-g on the body over a 24 hour period with 2 to 3 daily hours of countermeasures, in this case exercise.

History: Skylab, Shuttle and Mir

Experience developed through the history of the U.S. space program informs current understanding of the benefits of exercise countermeasures. From the beginning of long-term space flight, NASA has sought to incorporate effective countermeasures and improve those countermeasures as the data warranted.

The first U.S. experience with long-term habitation in Space included 3 missions on-board the Skylab space station. Missions included durations of 28, 59 and 84 days, and incorporated increasingly capable exercise countermeasures hardware. The first mission included only a cycle ergometer, to be augmented on the second mission by a handle/spring resistive exercise machine and kinetic rope pull. The third mission added a Teflon treadmill. Results showed that even with increasing mission durations, increased modes of exercise and increased exercise intensity on those later missions led to less loss of muscle than on earlier missions [4]. The Skylab crews demonstrated that it was possible to recover aerobic capacity by end of mission to pre-flight levels. Crewmembers with better post-flight functionality as compared to pre-flight required less recovery time.

Extended duration Space Shuttle missions included experiments to specifically evaluate the effects of microgravity on crewmembers and their response to countermeasures. While the flight durations only reached a maximum of 16 days, the amount of data obtained allowed more insight into the effectiveness of countermeasures. Shuttle exercise countermeasures included a cycle ergometer, a rower, and a treadmill. Results clarified that muscle atrophy occurs in missions of less than 16 days primarily in anti-gravity musculature [4]. Suited egress or EVA capability is dependent on aerobic fitness, investigations found. Results also identified the increase in aerobic stress to workloads post-flight. The treadmill demonstrated a capability to maintain leg strength, and aerobic exercise maintained aerobic capacity. Conclusions from these investigations led to the recommendation that for missions of 11 days or greater, exercise countermeasures should be required.

Experience gained during the joint U.S.-Russian Shuttle-Mir program substantially increased U.S. knowledge of long-term operations in Space. The length of the missions including 7 U.S. crewmembers averaged 140 days, with a maximum of 188 days. Exercise countermeasures available based on Russian flight experience included a treadmill, cycle ergometer, expander straps (elastic exercise straps), and a penguin suit. The penguin suit is a garment including elastic straps in specific locations requiring constant force from the wearer in order to maintain a specific orientation. Results from the Shuttle-Mir missions indicated that all crewmembers showed significant loss of bone mineral density in at least one region with significant variability between regions and between crewmembers [4]. The results also identified decreased muscle strength in the back and legs, as well as alterations in stability following return to the ground.

In 1995, NASA convened an expert panel, the Life and Microgravity Sciences and Applications Advisory Committee (LMSAAC) to evaluate the countermeasures program [15]. The panel's findings included that the available countermeasures did not adequately counteract the decline in muscle strength and endurance, which occurred to such a degree as to impair performance during EVA, especially on a planetary surface. The panel recommended heavy resistive exercise be incorporated to increase the effectiveness of the countermeasures program in reducing losses in muscle strength and bone mineral density in the most susceptible areas. The panel found the rate of loss of bone mineral density predisposed the crew to kidney stones, and an increased risk of lumbar spinal injury and disk herniation during post de-orbit activities. NASA incorporated these recommendations into design of the ISS countermeasures system.

Design of ISS Countermeasures System

The design of the ISS countermeasures incorporates knowledge gained from the previous experience with long term space flight. As mentioned before, the three primary components in the countermeasures system are a treadmill, a cycle ergometer, and a resistive exercise machine (See Figure 7). Each of these systems is similar to equipment used in fitness centers on the ground, but each has been modified to meet the unique requirements for transport to and operation in the ISS.

The countermeasures design is best analyzed in light of the functions of providing loading for bone and skeletal muscle, and the capacity for aerobic exercise. The countermeasures system must also mitigate effects other than the three discussed in this paper, such as decline in locomotor function and balance, which would impact a comprehensive evaluation of ISS countermeasures, but not be evident here. The three primary countermeasures sub-systems must satisfy together the three functions identified. The various training modes of running, cycling, and weight lifting, however, are not each specifically directed at a single function. Each contributes to several functions, and more efficiently towards some than others.

Mitigation of loss of muscle mass and subsequent loss of strength and endurance is accomplished by loading of the crewmember's muscles. All training modes provide this function; however, the resistive exercise machine is the most effective, since it provides the highest loads across all muscles of the body. The cycle and treadmill provide muscle loading of the lower body with a different set of characteristics that mitigate muscle loss to a lesser degree when employed alone.

The resistive exercise machine, again, provides the most effective mitigation to loss of bone mineral density, followed by the treadmill.

Both the treadmill and the cycle equally provide aerobic conditioning to crewmembers. This function is the only one for which a true redundancy exists, although even this redundancy, an unlike redundancy, is contingent on a crewmember's training protocol prior to flight. Since, a person's body adapts to the training method received, crewmember's must train roughly

equally between running and cycling prior to a mission in order to fully have the redundancy in this function.

As a whole the countermeasures system must accommodate crewmember capabilities from the 5th percentile Japanese female to the 95th percentile American male, the range of potential ISS crewmembers [16]. This wide functional envelope presents an engineering challenge to countermeasures design. These requirements together with restrictions on power use, load transmitted to ISS structure and total mass make design of an effective and reliable system difficult. These requirements with cost and schedule limitations led to compromises on the functional envelope in some cases. The resistive exercise machine, for example, provides only 300 lbs. of load, significantly less than the originally specified 500 lbs [17]. The cycle met its performance requirements. The treadmill achieved the majority of its functional envelope, but as we are to see in the next section, sacrificed reliability.

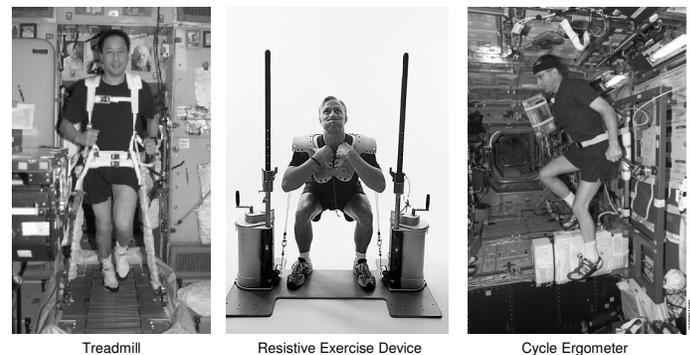


Figure 7: ISS Countermeasures Sub-systems

Evaluation of Effectiveness

The failure and anomaly reports provide a measure with which to evaluate the effectiveness of the countermeasures hardware in meeting their requirements in the operational environment. The availability of those hardware systems can be calculated using the dates in the problem reports for detection of the problem, the immediate impacts, and the implementation date for the resolution. Historical tracking logs provide important data on any operational constraints put in place following an anomaly or failure until resolution to determine the relative functionality during this period. The number of exercise opportunities or days is the basis of the calculation.

Data is then categorized based on the hardware being nominally functional, functionally degraded, or non-functional. Those categories can be more fully described as the hardware meeting at least 90% of its performance requirements, more than 10% of its performance requirements or less than 10% of its performance requirements respectively.

The figures 4, 5 and 6 below display the results of that analysis. Availability is calculated based on the number of exercise opportunities where hardware is functional divided by the total number of opportunities. Exercise opportunities are

analogous to mission days, since exercise is prescribed 6 days per week.

The ideal measure of effectiveness would be to evaluate the pre- and post-mission condition of ISS crewmembers, which is conducted on a regular basis. However, due to the small crew size, medical privacy concerns prevent this data from being presented mission by mission in comparison to the countermeasure availability at the time. This data is considered by the ISS flight surgeons, who then make recommendations for countermeasure system design and prescribe utilization by future crewmembers.

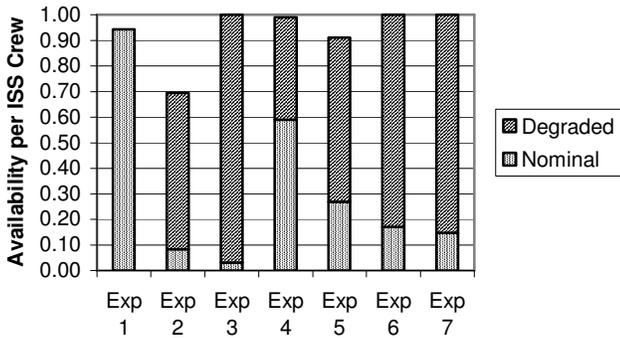


Figure 4: Availability of Treadmill during ISS Expeditions 1-7

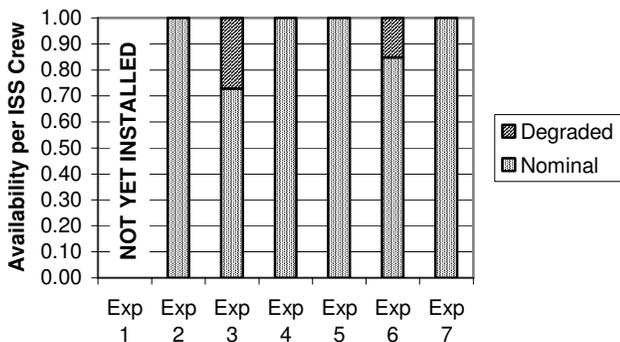


Figure 5: Availability of Cycle Ergometer during ISS Expeditions 1-7

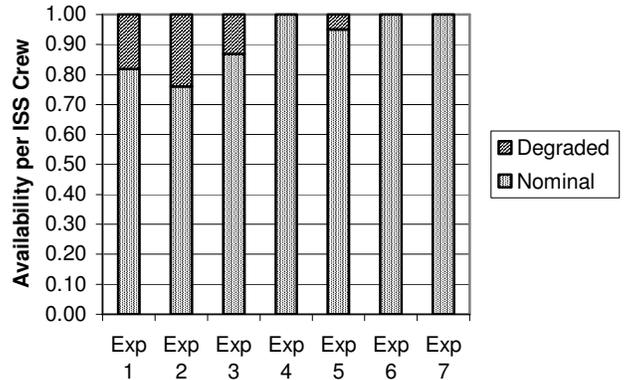


Figure 6: Availability of Resistive Exercise Device (RED) during ISS Expeditions 1-7

Incorporation of fault tolerance or functional redundancy cannot always be considered to be more effective. Although all other things being equal, redundancy does reduce the probability of loss of function. An example of this can be observed in the availability data for the resistive exercise device (Figure 6). Following Expedition 3, once engineers observed that the hardware reliability did not meet expectations, a spare set of hardware was maintained on board the ISS. The effects of this change are evident in the increased average availability following Expedition 3.

Desired availability is for no losses of function greater than 11 days per increment crew (to match recommendation for extended shuttle missions). That results in an availability of 0.9389 for a 180-day mission (0.9083 for a 120 day mission).

Since many exercise systems can also operate successfully in a degraded mode (50% of maximum exercise load or speed for example), a measure to gauge the availability of a functional plus degraded mission profile is desired. Assuming that 50% functionality extends the acceptable duration without nominal performance by a factor of 4, one arrives at a desired availability of 0.7556 for 180-day missions (0.6333 for a 120 day mission) for nominal performance with the remainder period sustained in a degraded mode.

To more appropriately consider the effectiveness of the countermeasure system in light of the overlapping functionality of the three main hardware systems, one must evaluate the functional availability. The availability for three countermeasure system functions: aerobic exercise, muscle loading and bone loading, appears below in Table 1. It should be noted that the countermeasures system must provide additional functions to be wholly successful such as locomotor and neurovestibular conditioning, but those functions are beyond the scope of this paper. The data for muscle and bone loading functions were combined, since they were identical.

This functional availability incorporates both primary and secondary capabilities of the various hardware systems. For example the treadmill provides aerobic exercise and also lower

body muscle and bone loading. In the area of muscle and bone loading, however, the treadmill is not as capable as the resistive exercise device (RED), so during periods of complete RED loss, the fully functional treadmill is counted as a 50% functional muscle and bone loading countermeasure. The cycle ergometer has similar overlapping functions with the treadmill and RED. This partially satisfies the 1-fault tolerance requirement identified earlier.

Only the aerobic exercise function was lost completely at any point, and it occurred briefly at the end of Expedition 1 and beginning of Expedition 2 (before installation of the cycle ergometer). Fifty percent (50%) functional capability was maintained in all other cases where failures occurred. According to the criteria established here, no missions show hazardously insufficient countermeasure availability. Two occasions warranted additional investigation for muscle and bone loading during Expedition 2 (0.7197 required) and aerobic exercise during Expedition 3 (0.6333 required), but both were acceptable, at least marginally.

Table 1: Availability of ISS Countermeasures by Function per Expedition Crew

<i>Mission</i>	<i>Function</i>	
	Aerobic Exercise	Muscle and Bone Loading
Exp. 1	0.9716	0.8652
Exp. 2	0.9427	0.7261
Exp. 3	0.7000	0.8500
Exp. 4	0.8777	1.0000
Exp. 5	1.0000	0.9467
Exp. 6	1.0000	1.0000
Exp. 7	1.0000	1.0000

Based on these results, one can identify failures that could have resulted in a hazardous loss of function, had the circumstances been different. These potential hazard causes or failure precursors identify the “weak links” in the overall countermeasures system and can be utilized to improve the reliability of the hardware design and the system failure tolerance or robustness.

A true investigation of the countermeasure effectiveness should be made by detailed examination of the capability of each crewmember with respect to the capability of the countermeasures equipment to determine functional availability, and then that data must be analyzed against the post-mission results in bone, muscle, and cardiovascular function loss for the specific crewmember. The criteria utilized here are arbitrary, although based on previous mission experience. They encompass a proposed measure of effectiveness with which to focus resources on future improvement in ISS countermeasures. Also, other countermeasure goals not investigated in this paper, such as mitigation of loss in locomotor and neurovestibular function play a significant role in the overall system design. Analysis including the comprehensive set of countermeasures functions must be complete to guide future decisions.

The hazardous situations mitigated by the ISS countermeasures hardware are chronic in nature, and make assessment of effectiveness difficult. Improvement in functional availability for the countermeasures system during later missions is the result of adapted operational management of those sub-systems which exhibited weaknesses earlier in the ISS experience. Additionally, the limitations of re-supply mass and volume mean that on-time arrival of spares and refurbished components may not occur in time to adequately protect for hardware failures. This limitation contributes a large amount of uncertainty in predicting future availability of countermeasures.

Future Improvements

Several efforts are currently underway to continue improvement of the microgravity countermeasures system for ISS and future long-term missions. Top among those project priorities are increased reliability and availability of the hardware systems, as well as increased capability in terms of expanding the physical training envelope for the crewmembers.

Two new countermeasure sub-systems are planned to advance the current ISS countermeasures suite. The first among these improved systems will be a new resistive exercise machine, with twice the load capability of the current system, and improved reliability. The second improved system is planned to be a new treadmill, which will increase reliability and expand the functional envelope beyond what the current treadmill can provide. These upgrades will alleviate the discrepancy of having better crewmember training capability than the machines can provide.

The current ISS countermeasure system provides redundancy in cardiovascular function by use of the cycle ergometer and the treadmill, and in bone and muscle loading function by the provision of spare RED hardware maintained on-board. This redundancy has thus far prevented a hazardous loss of function for the system while certain components have underperformed. Redundancy does not exist for all countermeasure functions outside of those presented in this paper, however, and future selection and design of new systems should take this into account. Priority among these should be the provision of locomotor and neurovestibular conditioning. Those functions are currently only provided by the treadmill, which has performed poorly. In addition to prioritization of a more reliable system, sufficient on-orbit supply of spare hardware to mitigate all single failure points or the future inclusion of a dissimilar system providing the same function should be pursued.

Future implementation of on-site monitoring hardware for critical health parameters such as bone mineral density would allow greater responsiveness, efficiency, and optimized design of the countermeasures system. While these parameters are routine to measure on the ground the systems are large and not readily adaptable to space travel. Currently in evaluation are instruments capable of providing this critical feedback to the management of countermeasures during the mission. This capability, once realized, would allow optimized use of the

countermeasures system for each individual's needs, both reducing risk for the overall population and possibly increasing the amount of available work-time for those found to be at lower risk.

CONCLUSIONS

Experience from the days of early spaceflight to the current ISS program demonstrates significant advancement in microgravity countermeasures. However, crewmembers continue to experience losses of functional capability, which in some cases approaches the level of an occupational illness. Safety hazards and risks to long term health increase in probability as the time spent in that condition increases. Current data points to the need for greater functional capability in the ISS countermeasures hardware in order to prevent crew functional decrements as currently experienced.

The availability of the ISS countermeasures hardware, while not falling below the criteria established in this paper, could be marginal at times. More intensive investigation of the hardware capability against crewmember capability and post-mission evaluations should lead to a better measure of risk to current ISS crews.

In looking at the ISS as a step in a broader human exploration program, the limitations on countermeasure success data currently prevents conclusions on appropriate countermeasures system design for longer term missions in microgravity (transportation to Mars) or in condition of 0.14 g (Moon) or 0.38 g (Mars).

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