Exercise Countermeasure Hardware Evolution on ISS: The First Decade

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The hardware systems necessary to support exercise countermeasures to the deconditioning associated with microgravity exposure have evolved and improved significantly during the first decade of the International Space Station (ISS), resulting in both new types of hardware and enhanced performance capabilities for initial hardware items. The original suite of countermeasure hardware supported the first crews to arrive on the ISS and the improved countermeasure system delivered in later missions continues to serve the astronauts today with increased efficacy. Due to aggressive hardware development schedules and constrained budgets, the initial approach was to identify existing spaceflight-certified exercise countermeasure equipment, when available, and modify it for use on the ISS. Program management encouraged the use of commercial-off-the-shelf (COTS) hardware, or hardware previously developed (heritage hardware) for the Space Shuttle Program. However, in many cases the resultant hardware did not meet the additional requirements necessary to support crew health maintenance during long-duration missions (3 to 12 mo) and anticipated future utilization activities in support of biomedical research. Hardware development was further complicated by performance requirements that were not fully defined at the outset and tended to evolve over the course of design and fabrication. Modifications, ranging from simple to extensive, were necessary to meet these evolving requirements in each case where heritage hardware was proposed. Heritage hardware was anticipated to be inherently reliable without the need for extensive ground testing, due to its prior positive history during operational spaceflight utilization. As a result, developmental budgets were typically insufficient and schedules were too constrained to permit long-term evaluation of dedicated ground-test units ("fleet leader" type testing) to identify reliability issues when applied to long-duration use. In most cases, the exercise unit with the most operational history was the unit installed on the ISS.

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ground testing due to its prior positive history during operational spaceflight utilization. As a result, developmental budgets were typically insufficient and schedules were too constrained to permit long-term evaluation of dedicated ground-test units ("fleet leader" type testing) to identify reliability issues when applied to long-duration use. In most cases, the exercise unit with the most operational history was the unit installed on the ISS.

Early Exercise Capabilities

The launch and assembly sequence of the ISS dictated that exercise countermeasures hardware initially be installed and operated in the Russian Service Module. A minimum set of hardware necessary to maintain crew physical fitness was identified. The first two devices selected to meet these requirements were: 1) the treadmill with vibration isolation and stabilization (TVIS) system, to enable walking and running in a 0-g environment without disturbing the microgravity environment or imparting excessive loads to its structure; and 2) the interim resistive exercise device (iRED), to support traditional resistive exercises typical of those performed on gym machines or with free weights.

Treadmill with vibration isolation and stabilization. The TVIS system design was based on the Shuttle extended duration orbiter treadmill, which previously had been flown and evaluated by crewmembers on multiple Shuttle missions. The TVIS was to be installed in the service module of the Russian segment of the ISS; however, significant modifications were required to meet the Russian segment requirements. These changes included adding a motor to enable both active and passive running modes, modification of the subject loading device (SLD) for better load application and control, advanced electronics/protocol control to allow automated exercise prescriptions, plus the addition of a powered vibration isolation and stabilization subsystem. The TVIS development was complicated by concurrent evolving requirements, an abbreviated development schedule, and significant budget limitations, with the result that minimal hardware was available for preflight ground testing.

Major challenges related to TVIS performance meeting medical requirements included: 1) a requirement that the SLD provide both a wide range of total load [0 to 100 kg (0 to 220 lb)] with $< 0.7\ \mathrm{kg \cdot cm^{-1}}$ ($4.0\ \mathrm{lb \cdot in^{-1}}$) load variation over the vertical range of motion during exercise; and 2) motor performance capable of 0 to 19.3 km/h (0 to 12 mph) for all SLD settings. Accommodating these requirements within the allocated power and volume constraints proved particularly challenging. There were additional inherent difficulties with validating 0-g running in a 1-G environment (Earth), with the result that complete verification required actual on-orbit trials. Various ground-based test towers for "horizontal" suspended running were developed to simulate 0-g running in the 1-G environment of Earth, and the full TVIS system was evaluated on one Shuttle mission (STS-81)].[2] The treadmill portion of the system was further evaluated on an additional Shuttle mission (STS-84) to aid in predicting performance characteristics.

The TVIS system was delivered to the ISS in May 2000 and on-orbit use began in December of that year (**Fig. 1**). Crew reports were initially positive regarding the physical and psychological benefits provided by TVIS exercise, but unanticipated performance anomalies arose during early TVIS operations:

- The actual subject loading on the slats (i.e., the treadmill belt) was significantly higher than predicted or tested in ground-based evaluations, which resulted in early belt/slat failures.
- Running style (e.g., foot force impact, vertical motion, wide versus narrow running stance, and gait) had a significant effect on the TVIS performance capabilities on orbit, both in terms of achievable speed and overall system stability.
- Motor control electronics were damaged early, resulting in speed limitations.
- Early unexpected wear on subject loading cables required the development of a contingency loading capability (i.e., use of the series bungee system).

Fig. 1. TVIS used by astronaut Sunita Williams, who ran the equivalent of the entire Boston Marathon on TVIS in 2007.

- Periodic refurbishment or replacement of hardware had always been planned; however, inspections of TVIS components returned to the ground revealed unanticipated hardware malfunction. These findings required additional redesign and in-flight upgrades to maintain an operational TVIS system.

These performance anomalies often required that the TVIS be operated in a reduced function mode [e.g., restricted belt speed, passive operation only (nonmotorized), or reduced subject loading] during the first 4 to 5 yr of ISS operations. U.S. crewmember use of TVIS ended in November 2009 with the installation of the second generation treadmill (T2). Russian crewmembers continued to use TVIS until they replaced it with a new Russian treadmill.

While TVIS performance issues were resolved eventually through design changes, spares, and replacement parts, they did require modifying exercise protocols to meet the constraints placed on the hardware operations. This situation illustrates the critical need for redundant exercise capabilities on ISS, back-up operational modes (even if less than optimal), and flexibility in designing exercise prescriptions.

Interim resistive exercise device. NASA and Russian experts agreed on the need to develop a spaceflight-unique device to meet resistive exercise requirements to counteract bone and muscle losses. The iRED was designed from the outset to be an interim solution, hence its name. It was designed to meet initial operational resistive exercise requirements, with the goal of accommodating more demanding research-driven requirements, such as higher precision and data acquisition, where possible within development constraints. An advanced resistive exercise device would be provided later to satisfy research requirements and expand operational capabilities.

Unlike the TVIS, no single heritage item was available, so early trade studies were initiated, evaluating Earth-based devices that derived their resistive loads from hydraulics, pneumatics, motors, bungees, springs, rotating flywheels, and other elastomers. A novel commercial device (SpiraFlex Inc., Kansas City, MO) was selected that provided loading using a stack of elastomer discs called "Flexpacks." Each disc consisted of an aluminum ring connected to an aluminum hub by elastomer straps. A shaft passing through the hub of each disc made it possible to incrementally select loads [approximately 11.3 kg (25 lb) per disc] based upon how many discs were used and how far the stack was rotated (stretching the elastomer straps). Concentric loading was created as the elastomer was stretched, eccentric loading occurred as the elastomer relaxed to its initial position. Various cable and pulley geometry allowed for the performance of numerous resistance exercises.

This existing COTs concept that was selected required extensive modifications to meet exercise countermeasure requirements. Specific challenges included: 1) expand load capability to a maximum of 227 kg or 500 lb [from 136 kg (300 lb)]; 2) provide for load adjustment in 2.3 kg (5 lb) increments; and 3) improve the force versus extension curve so that a more constant force would be provided throughout the range of motion for both eccentric and concentric forces. Once again, requirements unfortunately matured concurrently with hardware design and development and resulted in deleting several options (e.g., electronics/data storage, automated control).

Life cycle testing of the iRED training unit and 1-G performance evaluations associated with exercise protocols revealed several issues before delivery to the ISS:

- Load varied excessively over the range of motion and was highly dependent on speed or rate of the iRED cable extension.
- Loading during the eccentric phase of the movement was lower than concentric loads, which was a concern because many exercise specialists believed that eccentric loading was critical for effective resistance exercise training.
- Calibration of units was problematic as the absolute load provided at each setting was decreased over time.
- To prevent over-rotating the discs and damaging the elastomer, Flexpack rotation was limited and the maximum load capability was restricted to 136 kg (300 lb).
- Other engineering issues included binding, scraping, excessive cord wear, and delamination of the elastomer from the aluminum discs, which resulted in erratic loads and early failures.

The majority of these issues were discovered before delivery and design changes were implemented or operational controls developed prior to iRED installation and utilization on the ISS in December of 2000 (**Fig. 2**).

A review of the standard monthly on-orbit calibration data revealed issues with the load setting versus actual load, which indicated a mechanical binding issue. Operational controls (e.g., limits on loading, the length of the cable pulled from the canister, the total number of repetitions performed) were implemented to minimize hardware damage, and alternate/backup resistive items (bungee cords) were used to augment resistive exercise loading. The bungee cords were attached between the iRED harness and the iRED canister so that the loading from the iRED and the bungee cords was applied in parallel. When necessary, replacement parts were quickly provided and/or hardware repairs were completed such that iRED functionality was restored. The iRED continued to operate through 2008 with planned maintenance and resupply. Significant loading issues (i.e., the scraping of the Flexpacks against the inside of the canisters caused inconsistent and higher than expected loads) led to the decision to permanently stow the hardware just before delivery of the advanced resistive exercise device (ARED).

Expanded Exercise Capabilities

Exercise hardware was expanded to provide additional exercise options and capabilities with the installation of the U.S. Laboratory (Destiny) module in February 2001. A cycle ergometer with vibration isolation and stabilization (CEVIS) system was added to the complement to support aerobic and

Fig. 2. Astronaut Edward T. Lu wearing the shoulder harness while performing squats using the iRED equipment in the Unity Node on the ISS (2003).

cardiovascular conditioning and periodic fitness evaluations without disturbing the microgravity environment.

Cycle ergometer with vibration isolation and stabilization. The CEVIS system was derived from the Shuttle Extended Duration Orbiter Medical Project design, which originated from a cycle ergometer flown on the German Spacelab mission in 1985. The ergometer itself was developed by a Danish company and had significant flight history with multiple Shuttle flights. The complete CEVIS had also been flown and evaluated by crewmembers on several Shuttle missions. The CEVIS was a highly reliable system with extensive operational flight experience and no in-flight failures (**Fig. 3**).

Modifications were necessary to meet medical requirements, including enhanced control panel functions, data collection capability, and the ability to provide automated exercise protocols for the crewmembers. The CEVIS was installed in the U.S. Laboratory in March 2001 and functioned flawlessly for the first year of operation. An electronics failure in the control panel in March 2002 required use of the ergometer in an off-nominal mode, which was accommodated by the design that included both a CEVIS contingency controller and the ability to adjust workload manually, if necessary. Additional intermittent control panel and power issues required brief periods of operation in the manual or unpowered modes. However, CEVIS has operated nearly flawlessly and remains the cornerstone of exercise hardware in the U.S. Laboratory.

Fig. 3. Astronaut William S. McArthur, Jr., reading a checklist as he prepares to exercise on the CEVIS in the U.S. Laboratory module of the ISS (2006).

Advanced resistive exercise device. The ARED was designed and developed by NASA to replace the iRED and provide a long-term resistive exercise capability. The ARED provides appropriate magnitude and type of loading, ranges of motion, and the ability to record exercise session data to verify performance of exercise protocols. This device was designed to provide resistive exercise equivalent to the loads one would experience during heavy resistive exercise on Earth. Thus, the ARED includes simulation of both the constant load of the mass being moved and a certain amount of load variation with the acceleration of that mass (the inertial component).

The ARED uses a vacuum cylinder/flywheel assembly to provide this combination of constant and inertial resistance forces (**Fig. 4**). During exercise, the user moves a lever attached to the pistons inside the vacuum canisters, working against the force of the vacuum, which provides the constant resistance for the exercise. Resistive load is adjusted by changing the attachment point of the piston rods, thereby changing the length of the lever arm. Flywheels are used to simulate the inertial component of exercise that would be experienced on the ground, so that exercise feels as natural as possible.

The ARED incorporated multiple improvements relative to the iRED performance capabilities. Most importantly, the maximum achievable load was increased to 272 kg (600 lb) for bar exercises and overall range of motion was increased to 76 cm (30 in), which allowed higher loading for critical exercises such as squats. Exercises not requiring a bar can be performed with a cable over a range of motion of 193 cm (76 in) with loading up to 133 kg (250 lb; e.g., bent-over rows, upright rows, bicep curls, and tricep extensions, crunches). The consistency of eccentric/concentric loading was significantly improved, providing the equivalent of ~90% of the concentric load during the eccentric phase of movement for bar exercises. Ground-based testing

Fig. 4. Astronaut Lee Archambault performing an ARED workout in the Unity Node aboard the ISS (2009).

revealed that when performing exercises with the cable, the dynamic load profile varied from selected loads (eccentric loads were at ~75%, and concentric loads were at ~120% of set load).

The ARED electronics provide the capability to measure and record information such as force and displacement, exercise sets, and repetitions performed. This information can be accessed by the crew and later downlinked to the ground. The displays provide the capability for crewmembers to view their exercise prescriptions and monitor their progress during an exercise session. The data are telemetered to exercise physiologists and flight surgeons, permitting them to verify adherence to the exercise prescriptions, and to engineers to allow them to monitor cycle life performance of the ARED device.

An extensive ground mechanical life-cycle test program was initiated during development and remains in progress to this day. Experience gained with this ground unit will be helpful in predicting potential future anomalies. In addition, a man-in-the-loop (MILT) test was completed before ISS delivery. The MILT testing evaluated functionality, durability, and reliability of ARED as experienced by human subjects during bar exercises.[1] The result of this comprehensive human testing was a dramatic increase in reliability, deletion of operational constraints, and reduction of routine maintenance by a factor of 3 relative to that of iRED.

The ARED was delivered to the ISS in 2008. Only minor performance issues have been experienced since installation and initial operation of the ARED on the ISS. Relative to exercise implementation, these issues were predominately associated with the data collection instrumentation and load sensor readouts (load was accurately reflected on dial indicators to the crew, but the measurement transmitted from the load cells was inconsistent). The ARED operations have continued nearly uninterrupted, with minimal maintenance and periodic vacuum cylinder evacuation (to preserve accurate loading by the piston/vacuum motion). The ARED has provided the desired increased loads, better load characterization, vibration isolation, lower maintenance requirements, and greater ease of use and reliability.

T2 combined operational load bearing external resistance treadmill. Expansion of the ISS crew to six crewmembers in 2009 required an additional treadmill to accommodate the required daily exercise; with only one treadmill there would be insufficient time in the 8-h workday to schedule exercise for six crewmembers on the single TVIS system. The ISS operational experience with the TVIS (specifically, the lack of life-cycle testing before flight) established the goal of locating a reliable, widely used commercial treadmill device and then modifying it minimally for spaceflight.

The T2 combined operational load bearing external resistance treadmill (COLBERT) is based on a Woodway treadmill (Woodway USA, Inc., Waukesha, WI), which has been used extensively in major sports markets and is known to be mechanically robust and reliable (**Fig. 5**). A passive vibration isolation system design was selected (modified from the standard ISS payload rack isolation system) to allow using more of the total power budget for the treadmill motor. Thus, the T2/COLBERT can operate at the required higher speeds [up to 20.4 km/h (12.7 mph)], which are necessary to enable higher intensity exercise protocols with reduced time per session. However, the passive isolation system is effective only at exercise speeds greater than 5.6 km/h (3 mph). Although the T2/COLBERT running surface is shorter than that of TVIS, its greater width allows a more natural running style.

The subject loading system was also greatly simplified, using bungee cords rather than the active SLD on TVIS. Although this approach results in lower total loading and more load variation over the range of subject vertical motion, the tradeoff is a highly reliable system with essentially no maintenance requirements and sufficient loading [54.4 kg to 68.0 kg (120 to 150 lb)] for exercise. Development of an active SLD is being considered as a future upgrade to the T2/COLBERT and the hardware has been scarred to accommodate this possible improvement. The exercise restraint harness worn by the crewmembers was also improved to provide better load distribution and comfort.

The T2/COLBERT was initially installed during November 2009 in Node 2 and eventually moved to Node 3. There have

Fig. 5. Astronaut Nicole Scott running on the T2/COLBERT in the Node 2 aboard the ISS (2009).

been no mechanical issues associated with T2/COLBERT operations. Early power distribution issues restricted running speeds [no greater than 14.5 km/h (9 mph)], but full operational capability was quickly restored. Minor issues have been experienced with the computer control interface (it is the same computer interface used for ARED), but on-orbit workarounds (such as crewmembers manually recording their data) have ensured continued operation. Minimal maintenance is planned, consisting primarily of inspections with limited servicing. Multiple spare components on board should ensure uninterrupted operations.

The T2/COLBERT benefited both from its robust heritage in a gym setting and dedicated life cycle testing of all flight modifications. For example, the finish proposed for application to the running surface to meet initial materials requirements was found to induce early failures of the belt; hence, this finish was not applied to the eventual flight unit. Electrical wiring changes (to meet spaceflight requirements) and other modifications (such as adding a belt tensioner to allow for on-orbit tensioning of the belt over time) were evaluated as a part of this dedicated test program. In summary, a greatly simplified design, the use of hardware with proven ground heritage, and the implementation of a dedicated life cycle test program were instrumental to the success of the T2/COLBERT.

Complementary Hardware for Exercise Countermeasures Equipment

NASA and its International Partners have provided medical monitoring devices for ISS use in addition to the suite of exercise countermeasures hardware. These items support both operational exercise and science objectives; they are stowed in various locations on the ISS.

Blood pressure/electrocardiogram monitor. The blood pressure (BP)/12 lead electrocardiogram (ECG) monitor is capable of automated, noninvasive measurement of systolic and diastolic blood pressures, plus detection and display of diagnostic 12-lead ECG waveforms and heart rate. This equipment supports countermeasures and periodic fitness evaluations (PFEs), and was delivered to the ISS in September 2000. The BP/ECG is composed of three separate pieces of COTS hardware: the SunTech Tango BP Monitor (SunTech Medical, Inc., Morrisville, NC); the Schiller Cardiovit AT-10 ECG Monitor (SCHILLER AG, Baar, Switzerland); and the Zymed EASI Lead Box (Zymed Inc, Camarillo, CA). Minor power supply modifications were implemented to enable the hardware to use the ISS 10-V input power and to allow real-time data downlink of blood pressure and heart rate data through an onboard computer. These changes enabled ground-based medical personnel to observe crewmember tests in near real time.

No life cycle testing was planned as the BP/ECG had extensive commercial history and pedigree. Periodic anomalies have been associated with lack of data capture or transfer to the onboard computer and on to the ground during years of operation on the ISS. The BP/ECG remains operational today with no on-orbit maintenance required, but does require regular resupply of consumables (electrodes, razors, wipes, etc.) to support planned PFEs. It was originally planned to replace the BP/ECG every 3 yr to accommodate calibration requirements of its COTs subsystems, but this calibration has not been necessary to date.

Heart rate monitor. The heart rate monitor (HRM) is used during daily exercise, is one of the core devices for monitoring the cardiovascular status of crewmembers on orbit, and supports both operational and science requirements. The HRM arrived on the ISS in September 2000 and consisted primarily of COTS hardware manufactured by Polar Electro Inc. (Lake Success, NY), which included the watch receiver, chest strap with transmitter, and downloader box. Thus, a COTS device was employed again to obtain the latest generation hardware for minimal costs.

The receiver (watch) and chest strap required no modifications; however, the actual heart rate transmitter was modified to meet the medical requirement to transmit heart rate data to both the TVIS and CEVIS control panels (so that heart rate could be displayed and stored) and, in addition, to the heart rate watch receiver. The heart rate watch had significant spaceflight pedigree, as the COTS version had previously been certified and flown on both the Shuttle and the Russian space station Mir, so no life cycle testing was necessary. The initial HRM system supported ISS operations from 2000 until October 2007. Electronic parts obsolescence, both with Polar as well as the in-house transmitter modifications, and limited spare parts inventory eventually required updating to the HRM2. The HRM2 (also based on Polar hardware) was launched in February 2008 with enough spare parts included to cover anticipated ISS operational life.

ESA Hardware Contributions

Pulmonary function system and portable pulmonary function system. The pulmonary function system (PFS) was a collaborative development between ESA and NASA to provide an autonomous, multiuser facility. The PFS was designed to support human respiratory, cardiovascular, and metabolic research experiments. Measurements possible with the PFS include ventilation volumes, oxygen consumption, carbon dioxide production, cardiac output, diffusing capacity of the lung, forced expired spirometry, functional residual capacity, and other specialized tests of pulmonary function. The PFS is accommodated within the NASA Human Research Facility Rack 2 (HRF-2), located in ESA's Columbus module of the ISS. The PFS is comprised of photoacoustic gas analyzers, flow meters, a gas delivery system, environmental sensors, and the necessary interfaces to external equipment (**Fig. 6**). This system was launched in 2005, first used in 2006 during ESA's Astrolab mission, and led to an improved understanding of the operations required for appropriate cardiovascular fitness assessment, a capability that had been suboptimal until the PFS became operational.

The PFS was originally accommodated in the U.S. Laboratory. It was subsequently transferred into ESA's Columbus module in 2008. This effectively separated the equipment from CEVIS, the primary exercise device for use with the PFS. This situation demonstrated that a portable version of PFS would be inherently useful on the ISS to enable metabolic gas analysis and take related physiological measurements at any location on station.

The portable PFS, which evolved from the PFS, supports the same human physiological research capabilities, but includes additional features such as noninvasive blood pressure measurement, enhanced electrocardiogram capabilities, touch display, GO-switch, USB ports, and a number of analog and digital I/O ports. The portable PFS launched on the Japanese HTV-1 cargo vehicle in September 2009 and is stowed in the U.S. Destiny module. The initial suite of experiments took a variety of cardiorespiratory measurements during varying degrees of exercise up to maximum aerobic capacity on the CEVIS. The aims of these studies were to improve our ability to conduct cardiovascular fitness assessment in space and to develop a more complete understanding of human adaptation to the space environment.

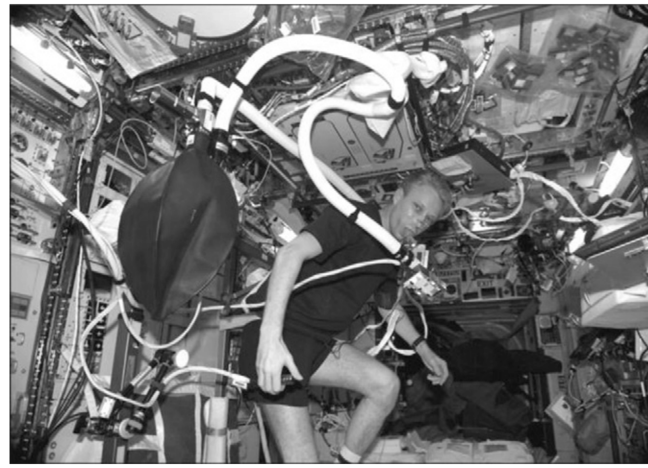

Fig. 6. Astronaut Thomas Reiter using the PFS to measure oxygen uptake (2006).

Conclusions

Living and working productively in space requires an understanding of the spaceflight-induced deconditioning of the human body and the development of effective countermeasures. Much has been learned during early spaceflight missions, and ISS missions provide a unique opportunity to study physiological adaptations to microgravity and potential countermeasures before embarking on exploration missions beyond low-Earth orbit. What we have learned to date through the use of operational countermeasure hardware and testing equipment will shape the development of countermeasures for extended stays in microgravity during future missions to Mars, the Moon, and asteroids. However, limitations on volume, mass, and power to accommodate the small volume of the next generation of space vehicles will require innovative approaches to countermeasure implementation that were not required in the relatively large volume available on the ISS.

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