Functional Fitness Testing Results Following Long-Duration ISS Missions

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INTRODUCTION: Long-duration spaceflight missions lead to the loss of muscle strength and endurance. Significant reduction in muscle function can be hazardous when returning from spaceflight. To document these losses, NASA developed medical requirements that include measures of functional strength and endurance. Results from this Functional Fitness Test (FFT) battery are also used to evaluate the effectiveness of in-flight exercise countermeasures. The purpose of this paper is to document results from the FFT and correlate this information with performance of in-flight exercise on board the International Space Station.

METHODS: The FFT evaluates muscular strength and endurance, flexibility, and agility and includes the following eight measures: sit and reach, cone agility, push-ups, pull-ups, sliding crunches, bench press, leg press, and hand grip dynamometry. Pre- to postflight functional fitness measurements were analyzed using dependent *t*-tests and correlation analyses were used to evaluate the relationship between functional fitness measurements and in-flight exercise workouts.

RESULTS: Significant differences were noted postspaceflight with the sit and reach, cone agility, leg press, and hand grip measurements while other test scores were not significantly altered. The relationships between functional fitness and in-flight exercise measurements showed minimal to moderate correlations for most in-flight exercise training variables.

DISCUSSION: The change in FFT results can be partially explained by in-flight exercise performance. Although there are losses documented in the FFT results, it is important to realize that the crewmembers are successfully performing activities of daily living and are considered functional for normal activities upon return to Earth.

KEYWORDS: spaceflight, functional fitness test, rehabilitation.

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The microgravity environment leads to losses of muscle strength and endurance during spaceflight[1,2,5,6] and long-duration stays from 4 to 6 mo that occur regularly on the International Space Station (ISS). Long-duration missions on board the ISS induce greater reductions in muscular function than shorter Space Shuttle missions with durations from 6 to 16 d.[3,4,6] Significant reduction in muscle function can be problematic when returning to Earth or during future exploration class missions beyond low-Earth orbit.

Before the first ISS mission, NASA developed a series of medical requirements to evaluate physiological changes due to prolonged stays in microgravity. Several medical requirements include measures of muscular strength and endurance. These measures were grouped together into a Functional Fitness Test (FFT) that is performed both pre- and postflight. This eight-measure FFT is used to measure functional strength and endurance of muscle groups for all ISS crewmembers. Results from this test are also used by flight surgeons and the Astronaut Strength, Conditioning, and Rehabilitation team to evaluate the effectiveness of in-flight countermeasures and document the progress of rehabilitation upon return from these missions. The purpose of this paper is to document FFT results from the first 25 expeditions and correlate this information with performance of in-flight exercise on board the ISS.

METHODS

A total of 32 (26 men, 6 women) crewmembers were evaluated with respect to functional fitness requirements in conjunction with their ISS missions. There were 3 crewmembers who flew 2 missions during the first 25 expeditions and their data for both

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flights were included in this analysis. All crewmembers were considered healthy; however, some individuals declined to perform a particular measure but completed the remainder of the test. For crewmembers who opted out of a test, the most common reason was either a current injury or history of an orthopedic injury to a specific joint or muscle. One crewmember was unable to complete the strength tests due to postural instability related to an inner ear condition.

Pre- and Postflight FFT

The FFT was performed both pre- and postflight to evaluate function and recovery to preflight norms. Initially the tests were scheduled approximately 60 d before flight, but as missions transitioned to Soyuz launches the tests were scheduled 60 to 90 d before flight. Postflight testing occurred between days 5 and 7 after landing. This postflight schedule remained consistent throughout the first 10 yr of ISS operations.

An astronaut initiated the testing sequence by performing a 10-min warm-up on a cycle ergometer, treadmill, or elliptical machine, followed by stretching as normally performed before a workout. The FFT consisted of the following eight measures:

Sit and Reach. Lower back and hamstring flexibility was evaluated using an Acuflex I sit and reach box (Novel Products, Rockton, IL). The astronaut was instructed to remove his/her shoes and place the feet against the footplate, then slowly reach forward bending at the hip with knees in a fully extended position and both hands one over the other. The astronaut reached forward as far as possible while holding the most distant point momentarily. The score was recorded as the furthest reach of three trials.

Cone Agility. Cone agility measured the ability to move and change direction quickly. Cones were placed at corners of a 4.572-m (15-ft) square and the astronaut was instructed to follow the pattern shown in **Fig. 1**. The total time was measured using a hand-held stopwatch and the score was recorded as the best of three time trials. The cone agility test was not a part of the original FFT and testing began with Expedition 9.

Push-ups. Push-ups measured the muscular endurance of the upper extremities. They were administered by starting in the standard up position with hands pointing forward and under the shoulders, head up, and back straight. The astronaut then lowered the body by flexing until the elbows were at 90°. The astronaut then returned to the starting position by extending his/her elbows. Resting was allowed in the up position. The score was recorded as the total number of push-ups performed in 2 min.

Pull-ups. Pull-ups measured either a muscular endurance or muscular strength, depending on the astronaut's baseline strength. This measure was conducted with either a pronated or supinated grip, but the grip was consistent throughout all test sessions. Astronauts were required to move through a full range of motion starting with the elbows fully extended and ending with the chin above the bar. The score was recorded as the total number of completed pull-ups.

Sliding Crunches. Muscular endurance of the abdominal core was assessed using this timed test. This measure began with the astronaut lying on his/her back, legs flexed to 90°, chin at chest, and arms at the side of the body. While pressing the lumbar spine into the floor and contracting the abdominal muscles, the hands slide toward the heels of the feet, and the arms and forearms remained on the floor with the chin on the chest for the entire movement. If necessary, astronauts were permitted to support their head with one arm. The score was recorded as the maximum number of sliding crunches completed in 2 min.

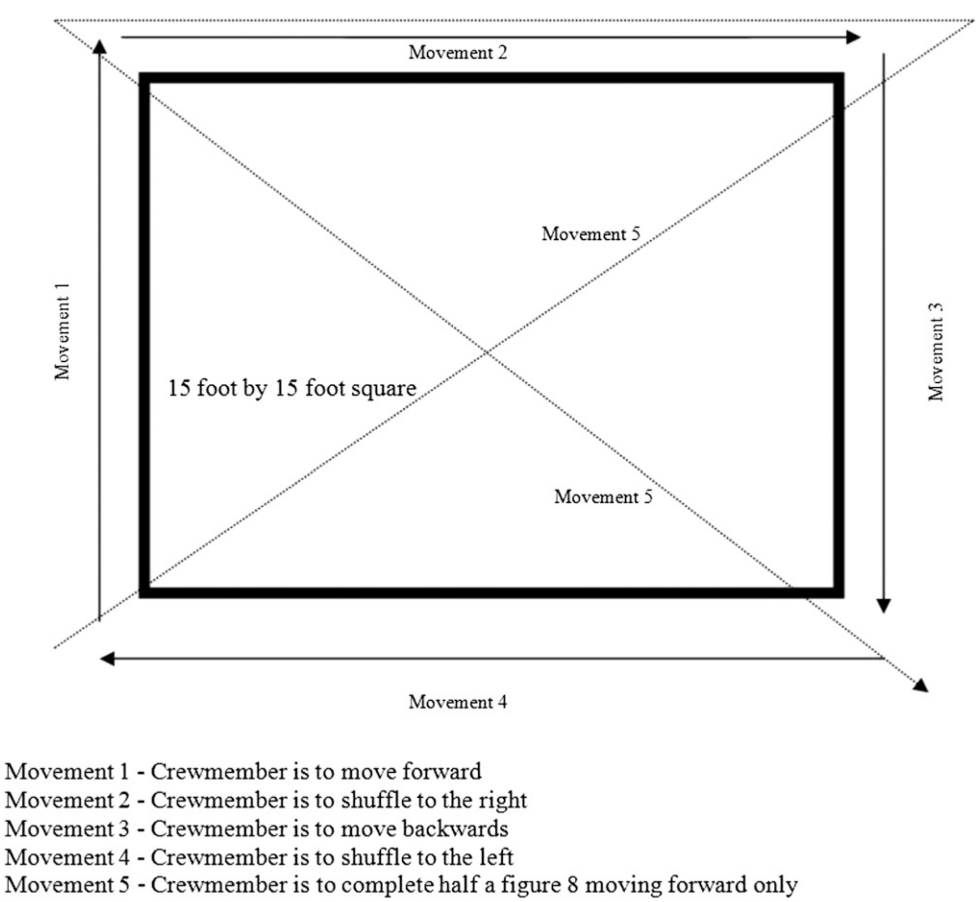

Fig. 1. Cone agility test.

Bench Press (1RM). A Cybex Smith Press Machine (Cybex International, Medway, MA) was used in the performance of this upper body strength measure. One repetition maximum (1RM) began with 2 to 3 warm-up sets at a subjective 30% load for 10 repetitions. A 3- to 5-min rest period was allowed between trials during which the astronaut was encouraged to stretch. The weight was increased conservatively, 10–20%, each set as the number of repetitions decreased until reaching one repetition. The load was increased until the astronaut failed to complete a lift. The bench press score was recorded as the maximum weight lifted for the last successful trial. (Modification: during some early missions 1RM tests were not completed; 4 to 6 RM tests were used with equations to estimate the 1RM weight.)

Leg Press (1RM). A plate-loaded Cybex squat-press machine (Cybex International, Medway, MA) was used in the performance of this lower body strength measure. The 1RM test began with a 2- to 3-min warm-up at a subjective 50% load for 10 repetitions. Between successful trials there was a 3- to 5-min rest period during which the astronaut was encouraged to stretch. The weight was increased conservatively, 15–20%, each set as the number of repetitions decreased until reaching one repetition. The load was increased 5–10% until the astronaut failed to complete a lift. The leg press score was recorded as the maximum weight lifted for the last successful trial. (Modification: similar to bench press, 4 to 6 RM tests were completed in some early missions and equations were used to estimate the 1RM weight.)

Hand Grip. This measured the isometric strength of the hands and forearms using a "Grip A" instrument (Takei and Co, Tokyo, Japan). Holding the instrument in one hand, the grip range was adjusted until the second joint of the forefinger was flexed to 90°. Rotating the dial counter-clockwise zeroed the indicated force. Standing upright, an astronaut griped the instrument and exerted full force while keeping the instrument at his/her side. At the completion of a trial, the astronaut switched hands and repeated for a total of three trials with each hand. The maximum score for each hand was combined for the total score. The handgrip test was not a part of the original test battery and was initiated on Expedition 9.

In-Flight Exercise

Exercise countermeasures were performed on board ISS during all missions. Exercise hardware included typical gym equipment that has been specially modified to perform in microgravity. Crewmembers were scheduled for 2.5 h of exercise, 6 d per week. The 2.5 h was typically divided into 1 h of aerobic training and 1.5 h of resistance training. These session times included hardware set-up, takedown, and post-exercise hygiene. Cardiovascular hardware included a cycle ergometer with vibration isolation system (CEVIS), two treadmills with vibration isolation systems (TVIS and T2), and a Russian ergometer (Velo). Resistance exercise was performed initially on the interim resistive exercise device (iRED) until a more advanced unit (designated as the advanced resistive exercise device [ARED]) was delivered to ISS during Expedition 18.

The CEVIS operated on ISS in a manner similar to a standard recumbent cycle found in a gym. The crewmember strapped themselves to a seat with a belt or held onto the frame to remain positioned on the cycle, wore cycling shoes and was able to quickly clip onto the cycle pedals, and began working out. The CEVIS was mounted on a vibration isolation system to minimize transfer of vibrations to the structure of the ISS.

The TVIS and T2 were the treadmill exercise countermeasures used on the ISS for exercise. On orbit, the crewmember wore a shoulder and waist harness and was pulled to the treadmill surface using either metal cables attached to preloaded springs or bungee cords. The T2 was modified from a commercial Woodway Path treadmill (Woodway, Waukesha, WI) that was designed to support walking and running exercise between 2.4 km/h (1.5 mph) and 20 km/h (12.4 mph). Both the TVIS and T2 were designed to minimize the transfer of dynamic forces caused by treadmill operations to preserve the microgravity environment of the ISS as well as minimize loads imparted to station structure.

Two different resistance exercise devices have been used during the past 10 yr of ISS operations. The original iRED was designed to prevent atrophy of the major muscle groups and to minimize bone loss in the microgravity environment. The iRED provided loading to the subject through cable connections to a pair of canisters, each of which contained stacks of elastomer discs (flex packs). These flex packs were attached to a pulley system and subject harness to mimic weightlifting on Earth. Each disc added an incremental resistance to the total force. The crewmember set the desired force and exercised by pulling against the resistance that resulted from twisting the elastomer discs within the canisters. With different bar, handle, and shoulder harness attachments, a crewmember could perform squats, dead lifts, heel raises, bent over rows, upright rows, military press, bench press, bicep curls, and triceps extension exercises. The major limitations of iRED were its maximum 136 kg (300 lb) total force and the elastic properties of the flex packs, which limited useful eccentric training. The iRED also lacked a vibration isolation system.

The iRED was replaced during Expedition 18 with the ARED, which simulates free weights by providing both a constant and inertial load. The ARED employs vacuum cylinders to create the resistive force. Onboard ISS, load ranges between 0 and 272 kg (600 lb) were available for bar exercises, while cable/rope exercises provided loads up to 68 kg (150 lb). Crewmembers performed both bar and cable/rope exercises to strengthen all major muscle groups. The ARED also incorporates a vibration isolation system to minimize forces transmitted to the ISS structure.

In-flight exercise data for each crewmember were collected for each exercise device and downlinked to the ground weekly. Initial processing of the data included formatting for a database and extracting the parameters included in **Table I**. Although the exercise data collection system was designed to minimize crew time requirements, multiple hardware failures have

Table I. In-Flight Exercise Data Parameters.

EXERCISE DEVICE	DATA PARAMETER
CEVIS	Exercise duration
	Work rate (W)
	Pedaling speed (rpm)
	Heart rate (bpm)
TVIS and T2	Exercise duration
	Speed of walking/running (km/h)
	Subject load (kg)
	Heart rate (bpm)
iRED and ARED	Exercises performed
	Number of sets
	Number of repetitions
	Load (kg)

resulted in missing data for several crewmembers. Table I lists the parameters that should have been collected for each exercise session. The mean resistive exercise loads for both iRED and ARED are noted in **Table II**.

Statistical Analyses

Pre- to postflight functional fitness measurements were analyzed using dependent *t*-tests. The criterion for statistical significance was set a priori at $P < 0.05$. All data are presented as the mean ± SD, unless otherwise noted. Relationships between functional fitness change scores and in-flight exercise measurements were evaluated using correlation analyses.

RESULTS

Pre- and postflight functional fitness results are summarized in **Table III**. Significant differences were noted with the sit and reach, cone agility, leg press, and hand grip measurements. There were no significant differences pre- to postflight for push-ups, pull-ups, sliding crunches, and bench press.

The relationships between functional fitness change scores and in-flight exercise measurements were evaluated and minimal to moderate correlations were observed for most variables. The sliding crunch test demonstrated the strongest correlation with the number of CEVIS sessions per week and this was only moderate at $\rho = 0.395$.

DISCUSSION

Differences in the FFT scores subsequent to ISS missions can be partially explained by in-flight exercise performance. "Sit and reach" measured lower back and hamstring flexibility and was significantly reduced postflight. This result is not surprising as it is difficult to stretch the lower extremity during spaceflight. Additionally, Simons demonstrated that during parabolic flight, relaxed body posture tends to approach a fetal position as the limbs move toward equilibrium.[7] Such postural changes have been verified in spaceflight[8] and a relaxed position would actually result in shortening the length of the hamstrings and lower back musculature. Both the inability to stretch and the altered body position during spaceflight may explain the decreased flexibility in the hamstrings and lower back musculature observed postflight.

Table II. Mean Loads for ISS Resistive Exercise.

MEASURE	*N*	MEAN LOAD (kg) μ ± SD	MEAN LOAD (lb) μ ± SD
Squats	34	103.5 ± 21.1	228.2 ± 46.6
Heel Raises	34	111.6 ± 24.3	246.1 ± 53.6
Dead Lifts	34	74.0 ± 18.8	163.2 ± 41.4

A second measure that showed significant differences pre- to postflight was the cone agility test. The mean time increased 1.36 s postflight, which was approximately 11% slower than preflight. This was not explained by differences in treadmill time, speed, or loading during flight. "Cone agility" is a complex movement requiring crewmembers to change direction, run forward and backward, and shuffle left and right. Although the ability to execute this type of complex movement is important to prevent injuries on the ground, it cannot be replicated with current ISS exercise hardware. Thus decreased performance was expected postflight and the difference of 1.43 s is approximately 1.5 to 2 steps.

Both the "leg press" and "handgrip strength" measurements were significantly lower after flight. This decrease was rather small for the leg press (-2.8% or approximately 9.07 kg [20 lb]) and handgrip (-4.9% or 5.6 kg [12.35 lb]). Previous testing in our gym has shown day-to-day variability in leg press 1RM scores ranging from 5 to 10%. Both these strength measures are statistically different compared to preflight but are not physiologically or functionally relevant and did not alter the postflight reconditioning protocols.

"Push-ups," "sliding crunches," and "bench press" measures were successfully maintained during the ISS missions. This was accomplished by integrating abdominal and bench press exercises in the exercise prescriptions performed on the iRED and ARED. Push-ups are not able to be performed on either resistance device but use the same musculature required for the bench press. Therefore by maintaining bench press capability, the ability to perform push-ups is also maintained. Exercise prescriptions are continually being altered and enhanced based on testing results to incorporate more complex exercises that will maintain multiple functional movement patterns.

Missing in-flight exercise data plagued our evaluation of the relationship between in-flight exercise and the resulting functional fitness measures. Therefore these correlation analyses are preliminary and further data are being collected to enable a more robust examination of this relationship. Operational status of the ISS exercise hardware further confounded these analyses. This exercise countermeasures hardware suite has experienced multiple failures during the 10 yr onboard ISS. Essentially no crewmember experienced a fully operational set of exercise hardware. Most crewmembers encountered limited performance of one or more of the exercise devices, making it difficult to determine the effectiveness of exercise prescriptions. In many cases, the status of the exercise hardware limited the

Table III. Functional Fitness Results.

MEASURE	*N*	PREFLIGHT μ±SD.	POSTFLIGHT μ± SD.	% CHANGE μ±SD.	*P*
Sit and Reach	31	17.29 ± 3.53	15.88 ± 3.49	-8.0% ± 9.5	< 0.001
Cone Agility	24	12.87 ± 1.02	14.23 ± 1.37	11.0% ± 11.8	< 0.001
Push-ups	34	48.35 ± 17.19	46.21 ± 16.7	3.1% ± 47.0	0.320
Pull-ups	30	9.13 ± 5.35	8.27 ± 4.35	-0.6% ± 41.2	0.146
Sliding Crunches	33	102.8 ± 30.8	100.0 ± 26.9	-0.9% ± 16.1	0.396
Bench Press (kg)	32	76.9 ± 22.3	76.8 ± 21.6	0.68% ± 9.9	0.971
Bench Press (lb)	32	169.6 ± 49.1	169.5 ± 47.6		
Leg Press (kg)	31	278.5 ± 60.6	269.8 ± 57.2	-2.8% ± 7.2	0.040
Leg Press (lb)	31	614.0 ± 133.6	594.8 ± 126.1		
Hand Grip	24	102.3 ± 19.7	96.7 ± 18.0	-4.9% ± 8.6	0.006

crewmembers' workouts more than their physical stamina or strength.

Although there are some performance decrements documented in the FFT results postflight, it is important to note that the crewmembers are successfully performing activities of daily living and are fully functional for normal activities upon return from the ISS. The main impairment during the first few days after landing was vestibular function, which can impact functional fitness testing. The vestibular impairment typically resolves quickly and the crewmembers begin to perform normal reconditioning workouts within 3 to 4 d of return. Reconditioning sessions are scheduled for 2 h a day, for 45 d following long-duration missions. Although outside the scope of this paper, the FFT is repeated at 30 d after landing and, at this time, all crewmembers have returned to or exceeded preflight fitness measurements.

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