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Postflight reconditioning for European Astronauts – a case report of recovery after six months in space

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Highlights

- Despite intensive training , most performance measures were impaired postflight
- Most functional abilities recovered 21 days postflight after daily exercise
- Powerful dynamic tasks (e.g. jumps) did not recover during the 21 day programme
- Reconditioning focussed on motor control and functional training for holistic recovery

Abstract

Background: Postflight reconditioning of astronauts is understudied. Despite a rigorous, daily inflight exercise countermeasures programme during six months in microgravity (µG) on-board the International Space Station (ISS), physiological impairments occur and postflight reconditioning is still required on return to Earth. Such postflight programmes are implemented by space agency reconditioning specialists.

Case Description and Assessments: A 38 year old male European Space Agency (ESA) crewmember's pre- and postflight (at six and 21 days after landing) physical performance from a six-month mission to ISS are described. *Assessments:* muscle strength (squat and bench press 1 Repetition Maximum) and power (vertical jump), core muscle endurance and hip flexibility (Sit and Reach, Thomas Test).

Interventions: In-flight, the astronaut undertook a rigorous daily (2-hour) exercise programme. The 21 day postflight reconditioning exercise concept focused on motor control and functional training, and was delivered in close co-ordination by the ESA physiotherapist and exercise specialist to provide the crewmember with comprehensive reconditioning support.

Outcomes: Despite an intensive inflight exercise programme in this highly motivated crewmember, postflight performance showed impairments at R+6 for most parameters, all of which recovered by R+21 except muscular power (jump tests).

Conclusions: Regardless of intense inflight exercise countermeasures and excellent compliance to postflight reconditioning, postflight performance showed impairments at R+6 for most parameters. Complex powerful performance tasks took longer to return to preflight values. Research is needed to develop optimal inflight and postflight exercise programmes to overcome the negative effects of microgravity and return the astronaut to preflight status as rapidly as possible.

1. Introduction

The effects of prolonged exposure to microgravity (µG) on the human body have been well studied [1-4] and include reductions of muscle volume and strength, bone mass and aerobic capacity [1] as the human body adapts to its new environment. Reductions of muscle strength and stability are associated with lower physical performance capacity and have a number of health implications [1, 5]. There are alterations in muscle activity, proprioception and posture [5], disc hyperhydration associated with fluid shifts [6] and cardiovascular changes [7]. This is not a "sick" but an "adapted" status, which may negatively affect physical performance and capacity, especially on return into Earth's gravity.

To counteract the effects of µG exposure [1, 3, 4] and to adequately prepare for return to Earth during Long (approximately six months) Duration Missions to the International Space Station (ISS), a rigorous inflight exercise countermeasure programme is implemented [8, 9]. Although the exercise prescription is individualised, the on-board constraints of ISS limit exercise to resistance training, treadmill and cycle ergometer training [9-11]. Despite the inflight programme, which is performed on a daily basis, deconditioning cannot be completely prevented. Thus, astronauts returning from LDMs require a postflight reconditioning programme, which begins one day after return (R+1), to restore their physical condition to preflight levels.

The astronaut population is a heterogeneous, but healthy and active population, displaying both traits of patients and of professional athletes in their postflight physical condition.

The aims of this paper are:

1. To briefly describe the physical exercise component of the European Space Agency's (ESA) postflight reconditioning programme;
2. To present a case report describing the postflight performance of one ESA crewmember following a LDM to ISS.

2. Case Information

The case of an active 38 year old (stature: 1.85 m; body mass: 83 kg) ESA astronaut who spent six months on ISS is described. He provided informed consent regarding the publication of his data for this case study. Ethics approval was obtained from the North Rhine (Germany) Medical Association. Findings from assessments pre- and post-intervention are presented in the outcomes section below.

3. Medical and Astronaut Fitness Assessment (AFA)

All ESA crewmembers undergo standardised preflight and postflight medical evaluations for long duration ISS missions (Medical Evaluation Documents, [MED], Volume B; document not publically available). During the 21-day postflight reconditioning period, these assessments usually occur twice on fixed dates and include the ESA Astronaut Fitness Assessment (AFA), and evaluation of aerobic capacity (Periodic Fitness Evaluation – PFE) and isokinetic muscle strength.

The aim of the fitness assessments is twofold: they provide direct performance feedback to the crewmember and exercise specialist for reconditioning and training plan design, and contribute to the overall long-term documentation of the countermeasures programme and astronaut health after space missions [12, 13].

The ESA AFA is composed of 10 tests targeting muscle strength and power, hip flexibility, balance and cardiovascular performance. The AFA is conducted at launch minus 52 days (L-52 days), and postflight at R+6 days and R+21 days to capture changes in functional fitness capacities related to space flight. For this case report we present a selection of results including maximal (1 RM) strength assessment on squat and bench press [14], muscular power assessed by vertical jump, core endurance and hip flexibility (Appendix 1)[15] [13]. Although additional measurements were taken, for the scope of this article the focus is on the results most relevant to the neuro-musculoskeletal system.

4. Interventions

4.1 European Space Agency Reconditioning Programme - Exercise Component

The ESA Space Medicine Office (SMO) reconditioning team for each crewmember is composed of an experienced exercise specialist/sport scientist and a physiotherapist.

This team supports crewmember health prior to, during and following the mission. The reconditioning programme integrates methods originating from physiotherapy and sports and exercise science, to provide a comprehensive, individualised 21-day programme. It includes a large spectrum of expertise, tools and methods to optimise the relatively short reconditioning time after flight. Exercise sessions focus on functionality, efficacy, safety and adequate intensity to promote a comprehensive neuro-musculoskeletal and cardiovascular response. Training locations are either at NASA's Johnson Space Center (JSC) Houston, USA, the Gagarin Cosmonaut Training Centre (GCTC) near Moscow, Russia, or at the European Astronaut Centre (EAC) in Cologne, Germany.

Exercise countermeasures to support the health and physical performance of crewmembers are composed of preflight preparation, inflight countermeasures and postflight reconditioning. The preflight phase is initiated on mission assignment, usually one to two years prior to launch, when individual-specific inflight protocols are developed. Preflight medical and fitness assessments are also implemented, one typically between one year to six months prior to launch, and another at L-30. Results are used as a baseline for comparison with inflight and postflight assessments to monitor the crewmember's condition and progress.

On-board ISS, daily 2-hour (2.5 hrs, including set-up time) intense countermeasure exercise is performed, guided by the exercise specialists ([8, 13, 16]). Since the inflight exercise countermeasures programme is not yet fully able to prevent deconditioning, a 21-day postflight reconditioning programme is undertaken. The objectives of the daily postflight intervention are to:

1) Prevent long-term health problems or injuries;
2) Return the crewmember to preflight physical condition, as assessed by postflight medical and fitness assessments.

4.2 Postflight physical exercise reconditioning concept

The present case report focuses of the physical activity and sport component of the ESA reconditioning programme, which is complementary to the physiotherapy concept reported by Lambrecht et al. in this special issue of *Musculoskeletal Science and Practice* [17].

The reconditioning sessions are closely coordinated between the exercise specialist and the physiotherapist. Large differences occur in postflight condition between astronauts, so sessions are adapted for the individual in terms of their complexity and intensity, and include additional training techniques. During the daily 2-hour sessions, the first hour is dedicated to physiotherapy in a classical treatment room, and the second hour used for physical training with the sport scientist. During the first week, exercises are performed in a swimming pool in coordination with gym sessions. The feeling of neutral buoyancy in the water is perceived as comfortable by astronauts, reminding them of the absence of body weight in microgravity. As the crewmember progresses, gym time *vs*. pool time increases, and physiotherapy exercises are also performed in the gym. In the main phase of the reconditioning, more time is spent in the gym performing resistance exercises than in the pool or in the physiotherapy room.

The ultimate goal is for the astronaut to perform safe and effective weight lifting training, exercises and sports activities that he/she performed before the mission. At the end of the reconditioning period, sessions should be at or near preflight intensity. The concept then aims to support a continued neuro-musculoskeletal regeneration process over the following months. Since this process cannot be monitored as closely by the ESA specialists, an individual exercise programme for unsupervised training is provided to each crewmember to continue training safely, with the goal of maintaining and/or improve health and fitness after the supervised reconditioning. The training incorporates exercises (Appendix 2,4) that are individualised to each crewmember and therefore vary in timing and intensity. The order as listed is applicable for most crewmembers.

The scheduled interventions and physical fitness assessments in the postflight period are shown in Table 1.

Table 1. Sequence of interventions and assessments until R+21 for all ESA crewmembers

Timeline	**R+0**	**R+1**	**R+2**	**R+3**	**R+4**	**R+5**	**R+6**	**R+7**	**R+8**	**R+9**	**R+10**
Intervention	Rehab	Rehab	Rehab	Rehab	Rehab	Rehab	Rehab	Rehab	Rehab	Rehab	Rehab
Fit test					PFE	Isokin	AFA				

Timeline	R+11	R+12	R+13	R+14	R+15	R+16	R+17	R+18	R+19	R+20	R+21
Intervention	Rehab	Rehab	Rehab	Rehab	Rehab	Rehab	Rehab	Rehab	Rehab	Rehab	Rehab
Fit test				PFE	Isokin						AFA

R+, Return date +number of days; AFA, Astronaut fitness assessment; PFE, Periodic Fitness Evaluation (Aerobic Capacity Evaluation), Isokin, Isokinetic measurement

4.3 Exercise Programmes Undertaken

4.3 1 Preflight training

During the preflight phase, ISS specific inflight training protocols (resistance training, cycle ergometer and treadmill) were prepared by the exercise specialist and in parallel, the ESA crewmember performed daily physical exercise for general fitness and Triathlon training. The preflight AFA was conducted 52 days prior to Launch (L-52 days). The crewmember was trained on flight-like ISS exercise hardware, with a focus on motor control, to be prepared for reduced proprioceptive feedback and altered muscle activation when exercising in µG [18] [19].

4.3.2 Inflight training

The astronaut performed daily intense and comprehensive training throughout the mission. He completed a total of 341 exercise sessions during his 6 months stay on ISS, of which 44% were dedicated to resistance training. Inflight physical condition, with the exception of cardiovascular performance on the cycle ergometer and training prescriptions, was not measured, since suitable methods are not yet available.

4.3.3 Postflight training

Reconditioning sessions were conducted along with medical and physical fitness assessments. Initially, ESA specialists implemented the reconditioning at NASA's Johnson Space Center (JSC) astronaut gym. Training followed the ESA programme outlined above (section 4.2) and the crewmember's specific postflight reconditioning is shown in Appendix 3.

5. Outcomes

The astronaut's compliance with inflight countermeasure exercise was high. His at L-60 days preflight peak VO_2 of 45.2 ml·kg^{-1}·min^{-1} ('excellent' compared to his age group according to ACSM guidelines [20]; internal confidential medical report) indicated that he was an active individual. Furthermore, during the postflight phase, he performed additional exercise to the supervised reconditioning programme and completed an 'Iron Man' event eleven months after return from space.

5.1 Astronaut Fitness Assessment results

In general, the crewmember's postflight physical performance measurements were reduced at R+6 and had partially or fully recovered at R+21 (Table 2). The most notable deficits were in jump performance and flexibility.

The height (cm) and force (N) of all three types of jump, countermovement (CMJ), squat (SJ) and drop jump (DJ), were reduced at R+6, with greatest deficits for both parameters seen in the DJ (height -31%; force -34%). None of the parameter for any jump had recovered by R+2, except CMJ force. The sit and reach flexibility results showed a 16% decrease from preflight distance at R+6, which had recovered to -3% a decrease by R+21. Muscle strength (1RM and bench press) was less affected, reducing by approximately 8-9% at R+6 and recovering to a 1-3% deficit by R+21 compared with preflight measures. Core muscle endurance was preserved from preflight (260 sec) to R+6 (262 sec, +1%) and R+21 (251 sec, -3%). Balance test results for one leg standing with eyes closed for 15 seconds were reduced at R+6 and R+21 (9 secs and 8 secs respectively) and eyes closed on toes was 10 secs at R+6 and had recovered to 15 secs at R+21.

Table 2. Astronaut Fitness Assessment results comparing preflight (L-52) against postflight (R+6, R+21)

AFA	Parameter	L-52	R+6	R+21	% P#1	%P#2
Body	Body Mass [kg]	81	83	83	2%	2%
	BMI [bm/height]	24	24	24	0%	0%
1 RM	Squat [kg]	148	134	147	-9%	-1%
	Bench [kg]	108	99	105	-8%	-3%

Jumps height	CMJ [cm]	41	33	35	-20%	-15%
	SJ [cm]	35	32	32	-9%	-9%
	DJ [cm]	35	24	30	-31%	-14%
Jumps PF	CMJ [N]	2070	2141	1827	3%	-12%
	SJ [N]	2143	1782	1689	-17%	-21%
	DJ [N]	4727	3120	4381	-34%	-7%
Core endurance	Ventral [sec]	260	262	251	1%	-3%
Hip flexibility	Sit'n'Reach [cm]	37	31	36	-16%	-3%
	TT right [deg]	32	33	27	3%	-16%
	TT left [deg]	30	30	23	0%	-23%

AFA, Astronaut Fitness Assessment; L-52, 52 days prior launch; R+6/21; 6/21 days after return; 1 RM, repetition maximum; bm, body mass; BMI, body mass index; *CMJ, countermovement jump; SJ, squat jump; DJ, drop jump; TT. Thomas Test; PF, peak force*

6. Discussion

The pre- to postflight comparisons in the present data show the astronaut had neuro-musculoskeletal impairments, particularly in the first week after return to Earth. Most, but not all aspects of performance recovered to preflight values by the end of the 21 day reconditioning phase, despite a high level of crew compliance to physical exercise before and during the mission, and despite good core endurance and peripheral strength. These observations support the reported findings in astronauts that, even in high performing and well-trained crewmembers who adhere to rigorous inflight countermeasures, it is not possible to preserve physical performance completely to prepare for everyday activities on return to Earth [21]. Intensive postflight reconditioning for 21 days was sufficient for most but not all aspects of function to recover fully.

6.1 Squat and Bench strength (1RM strength tests)

Loaded squatting is a complex movement requiring motor control and strength when lifting load against gravity. Squat 1RM performance was reduced by 9% at R+6, but recovered by the end of the reconditioning period. This deficit is larger to average values reported by NASA on similar, although not identical (leg press) postflight assessments (-2.8%), with day-to-day changes of 1 RM scores between 5-10% but they are not considered as physiologically relevant [12]. Squats showed slightly larger decreases than bench press for this crewmember, but also a very rapid and complete recovery. The crewmember's absolute pre-flight performance for bench press and sit and reach at R+6 were greater than average values reported by NASA for ISS crewmembers [12] but testing protocols between NASA and ESA vary slightly, so the results should be interpreted with caution.

In the postflight phase, while the body is re-adapting to gravity, crewmembers and exercise specialists are conservative when applying external loads to the body while postural stability is not yet fully restored [5].Weight lifting training is usually inserted into the programme after R+5 or even later for most crewmembers. In the present case, controlled light load resistance exercise (also in preparation of the fitness assessment) was implemented earlier than usual at R+4, which is exceptional. The second postflight squat measurement (R+21 in Table 2) showed that the crewmember was able to lift similar weights as preflight, indicating successful reconditioning for that task.

Isokinetic testing on NASA astronauts has shown that reduction in knee extensors is greater than that of the flexors [21], which is consistent with extensors undergoing greater atrophy than flexors in MRI studies [22].

In addition to muscle strength, motor control may be an important factor for crew performance. Astronauts usually feel uncomfortable performing loaded squats shortly (R+6) after their mission, and therefore results may also be associated with a more careful and conservative approach to these exercises. As confidence, and postural stability and movement improve during reconditioning, this situation improves and thus may, in part, explain some of the apparent recovery in performance between R+6 and R+21.

6.2 Muscular power/Jump

Jump height was reduced at R+6 (between 9-31% for the three different jumps) and was not fully restored and even showed decreases in the second measurement (R+21) for CMJ and SJ peak force. This prolonged deficit may not be due entirely to loss of power but neuromuscular ability, as jump test performance is strongly dependant on inter-muscular coordination and technique proficiency [23].

Given that jumping is a complex task requiring stability, strength and movement control, the supervised postflight programme may be too short to achieve full recovery. Dynamic and powerful movements are introduced relatively late in the programme to allow spinal/trunk stabiliser muscles to recover prior to doing exercises requiring complex motor control. Astronauts do not perform fast or explosive movements/exercise such as jumping or sprinting whilst on ISS, nor do they need to perform any work tasks that require maximal or near maximal effort [24]. Instead of using their legs to move through the station, they use their hands. Movement patterns adapted for µG need to be "unlearned" upon return to Earth, and previous, gravity-adapted movement patterns and reflexes must be re-acquired to successfully perform jumps.

Anecdotally we observe that many crewmembers are unable to perform a valid (*i.e.* movement controlled) jump at R+6. The ability to control the motion is critical. Prior to any loaded movement of the lower extremities, such as jumps, trunk muscles, especially deep abdominal/muscle corset muscles (transversus abdominis, then multifidus), are sequentially activated, preparing for the movement [23]. The sequential activation of muscle influences jump height [25]. Correctly coordinated contraction of leg and trunk muscles, for any powerful motion in daily life, needs to be retrained to ensure that crewmembers can respond to hazardous situations. This is a critical safety aspect of the programme, even with fit individuals.

These observations appear to complement findings from another case study of the same crewmember, which measured the intrinsic trunk muscles (multifidus, transversus abdominis, internal oblique) using ultrasound imaging and observed that muscle size was maintained at L2-L4, but not at L5 [19]. The phenomenon of muscle atrophy at the level of L5 after longer phases of inactivity occurs not only in bed rest participants and astronauts [6, 26], but is also in highly trained professional athletes [27]. Incomplete re-training of intrinsic back muscles after inactivity may lead to compensation by superficial muscles without their inherent ability to effectively stabilise and protect spinal segments.

6.3 Flexibility

Hip flexibility was also impaired in the present astronaut, perhaps due to the lack of eccentric motion in µG which is required for walking, running or jumping [28]. Stretching exercises are performed by some crewmembers on ISS in preparation for strength training. Specific stretching sessions are not prescribed by exercise specialists, but are encouraged. The sudden transition back to Earth's gravity may contribute to overall muscle stiffness compromising flexibility as a reaction to the new load/gravitational environment, which may persist during the 21 day postflight exercise period. Relaxation and flexibility training, involving fascial training [29] in parallel to individual physiotherapy treatments, was implemented with this astronaut as part of his postflight programme.

6.4 Core muscle endurance

Core muscle static endurance in a given position (measured in seconds) did not change significantly from pre to postflight, although changes in strength (squat, bench press, and jumping) were observed at R+6. The ventral core test requires the ability to maintain continuous muscle contraction in a bench-like position, but it is not a complex or dynamic motion such as a jump. Other tests of core endurance performed in different postures were found to be unreliable [12] so are no longer used as part of the AFA.

6.5 Balance

The Balance results of the AFA appear rather inconclusive. The reliability of this test showed high errors between measurements that are probably not attributable to performance changes [13]. Therefore the current test might not be suitable for assessing balance sufficiently for this occupational group and more appropriate tests are needed.

Regardless of the findings, the physical performance of this crewmember was never regarded as critical given his good overall condition. Complete recovery was expected throughout the months following reconditioning due to his ambitious personal exercise schedule.

6.6 Future direction

The ESA postflight reconditioning programme is based on the best evidence available from terrestrial rehabilitation [17]. Future exploration missions of up to three years, such as to Mars, will be even more challenging to recover from and require research to develop optimal reconditioning programmes. Inflight 'Preconditioning' programmes may also be needed inflight, to prepare for planetary surface exploration during these missions [30]. Parallels with deconditioning in areas of terrestrial rehabilitation, such as sports injuries, neurological disorders and intensive care may be helpful to draw on in the absence of studies on astronauts [31]. Simple, non-invasive ways of monitoring neuro-musculoskeletal function are also needed. Conducting research in the relatively small astronaut population is challenging and possible solutions are discussed by Beard and Cook [32].

7. Conclusions

This case report has highlighted that, despite a high degree of compliance with arigorous daily inflight exercise countermeasure programme, postflight neuro-musculoskeletal impairments still occur. The recovery process was not complete at the end of the 21-day reconditioning programme for dynamic powerful movements, whereas muscle strength and core muscle endurance recovered more fully, suggesting that motor control of movement may require more specific/further retraining. Research to develop optimal reconditioning programmes for longer exploration-type missions is needed urgently.

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Abbreviations

AFA	Astronaut Fitness Assessment
ARED	Advanced Resistive Exercise Device
CSA	Canadian Space Agency
EAC	European Astronaut Centre
ESA	European Space Agency
GCTC	Gagarin Cosmonaut Training Centre
ISS	International Space Station
JSC	Johnson Space Center (NASA)
L-	Launch date minus (days to launch)
L	Vertebra level (spine)
LDM	Long Duration Mission
MCE	Motor Control Exercise
NASA	National Aeronautics and Space Administration
PFE	Periodic Fitness Evaluation
R+	Return date plus (days after return)
RM	Repetition maximum
µG	Microgravity