The role of physiotherapy in the European Space Agency strategy for preparation and reconditioning of astronauts before and after long duration space flight

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Highlights

- The ESA Programme involves tailored physiotherapy following evidence-based principles
- Live video feedback to astronauts helps optimise exercise performance and safety
- Postflight reconditioning parallels many aspects of terrestrial physiotherapy

Abstract

Spaceflight and exposure to microgravity have wide-ranging effects on many systems of the human body. At the European Space Agency (ESA), a physiotherapist plays a key role in the multidisciplinary ESA team responsible for astronaut health, with a focus on the neuro-musculoskeletal system. In conjunction with a sports scientist, the physiotherapist prepares the astronaut for spaceflight, monitors their exercise performance whilst on the International Space Station (ISS), and reconditions the astronaut when they return to Earth. This clinical commentary outlines the physiotherapy programme, which was developed over nine long-duration missions. Principles of physiotherapy assessment, clinical reasoning, treatment programme design (tailored to the individual) and progression of the programme are outlined. Implications for rehabilitation of terrestrial populations are discussed. Evaluation of the reconditioning programme has begun and challenges anticipated after longer missions, e.g. to Mars, are considered.

Key Words

Physiotherapy; microgravity; spaceflight; astronaut reconditioning; exercise; low back pain

1. Introduction

The requirements of the human body, in particular the neuro-musculoskeletal system, are very different in space than on Earth. Interestingly, physiological spaceflight data suggest that it is more difficult to return to gravity than to adapt to microgravity conditions (Payne et al 2007). On Earth, the line of gravity normally passes through the ventral part of the L3 vertebral body (Richter & Hebgen, 2006), ensuring optimal load transfer). In microgravity, musculoskeletal adaptations are appropriate to that environment but this has major effects on muscle function and posture. Astronauts move in a predominantly flexed position and the centre of mass shifts posteriorly (Baroni et al, 2001), with increased recruitment of flexor muscles and a loss of extensors (Fitts et al 2001; Fitts et al 2000). A shift of muscle fibres types from tonic (type 1) to phasic (type 2) occurs (Fitts 2001). Graviceptors, which are sensory receptors that contribute to providing a neural representation of the direction of gravity, with respect to the gravity vector (Binder 2009), no longer function in microgravity. The astronaut therefore receives less information about his/her posture and has to rely on vision and feedback from dynamic receptors.

Prolonged microgravity has negative effects on muscle strength and endurance, motor control, coordination and balance (Layne et al, 2001), which may place the astronaut at higher risk of injury. In the spine, primarily lumbar, intervertebral discs absorb more water (hyperhydration) than on Earth (Belavy et al 2016), which can be associated with low back pain (LBP) inflight but is short-lived and has been reported in 70% of astronauts without a history of LBP and 100% of those with a history of LBP (Pool-Goodzwaard et al 2015). The effects of microgravity on the intervertebral disc must be considered to allow safe re-loading of the spine postflight, as the astronaut must readapt abruptly to gravity on return to Earth. The incidence of herniated nucleus pulposus is 4.3 times higher in astronauts than in terrestrial populations, predominantly in the period immediately following return to Earth (Johnston et al 2010).

Since 2006, ESA has built its multidisciplinary team responsible for astronaut preparation, inflight management whilst on the International Space Station (ISS) and reconditioning after return to Earth. The physiotherapist and sports scientist are jointly responsible for the neuro-musculoskeletal health of astronauts. The ESA programme is based on specific principles and tailored to meet the needs of the individual astronaut. Evidence-based aspects central to physiotherapy practice (assessment, clinical reasoning and treatments) are integral to the management of astronauts.

The aim of this clinical commentary is to describe the ESA physiotherapy approach developed for astronauts who experience long-duration space flights.

2. The ESA Astronaut Programme

Members of the multidisciplinary team are involved throughout the three phases of the mission cycle of an astronaut in the ESA programme. The team includes flight surgeons, a psychologist, biomedical engineers, a nutrition specialist, a physiotherapist and sports scientist. Only the programme provided by the physiotherapist and sports scientist are discussed in this commentary. The sports science components are illustrated in a case report by Petersen et al (2017).

2.1 Preflight Training

The goals of preflight training are to a) familiarise the astronaut with the Inflight Training Programme; b) treat any pre-existing neuro-musculoskeletal conditions; c) prepare the astronaut for space; d) conduct preflight measures.

Flight preparation takes place over two years in three locations: The European Astronaut Centre (EAC) at the European Space Agency (ESA), Cologne, Germany; Johnson Space Center (NASA), Houston, USA; and Gagarin Cosmonaut Training Centre (RSA), Moscow, Russia. The ESA physiotherapist and sports scientist see the astronaut 10-20 times, depending on the astronaut’s availability to educate them about the neuro-musculoskeletal changes that will occur and how these will be managed. This period is also crucial for building trusting relationships between the astronaut and training specialists, to maximise compliance.

The initial physical examination includes assessment of posture, motor control and functional movement, as well as in-depth assessment of joints/regions with pre-existing conditions. Physiotherapy modalities which may be appropriate at this stage include manual therapy, motor control training, elements from proprioceptive neuromuscular facilitation (PNF), fascial treatment, etc., as appropriate. If techniques such as kinesiotaping are required, the astronaut is taught self-application for use on the ISS. A home programme is given to the astronaut, which is monitored and progressed as necessary.

Ultrasound imaging was used for the last four missions to assess size and the ability to voluntarily contract antero-lateral abdominal and paraspinal muscles (Hides et al 1995, Hides et al 2007, Wallwork et al 2007). This allows comparison of preflight measures with those taken postflight and post-reconditioning (Hides et al 2016a). Ultrasound imaging is also used to provide feedback of muscle contraction if retraining is required (Van et al 2006).

The astronaut is familiarised with the Advanced Resistive Exercise Device (ARED), a strength training exercise countermeasure on the ISS (Figure 1). The goal is to optimise and practise movement patterns that will be performed on the ISS, although exercising will feel very different on the ISS because of microgravity and lack of proprioception. The focus is on optimising postural control whilst performing exercises on the ARED, with attention paid to the position of the lumbo-sacral junction (avoiding posterior pelvic tilt), thoraco-lumbar junction (avoiding extension) and correct positioning of the cervico-thoracic junction.

Fig 1 Advanced Resistive Exercise Device (ARED) Training at the Johnson Space Center, Houston. The Physiotherapist and Sports Scientist help the astronaut to optimize performance of exercises on the (ARED) device. (Photograph courtesy of ESA)

2.2 In Flight Training on the ISS

Inflight, the astronaut is required to perform two hours of training each day to mitigate the known negative effects of microgravity on the neuro-musculoskeletal system. For muscular and cardiovascular endurance, a cycle ergometer or treadmill is used. For strength training and loading of skeletal structures, the ARED is used. The ARED uses adjustable resistance piston-driven vacuum cylinders along with a flywheel system to simulate free-weight exercises in gravity, to work all the major muscle groups including squats, dead lifts, and calf raises (Figure 2).

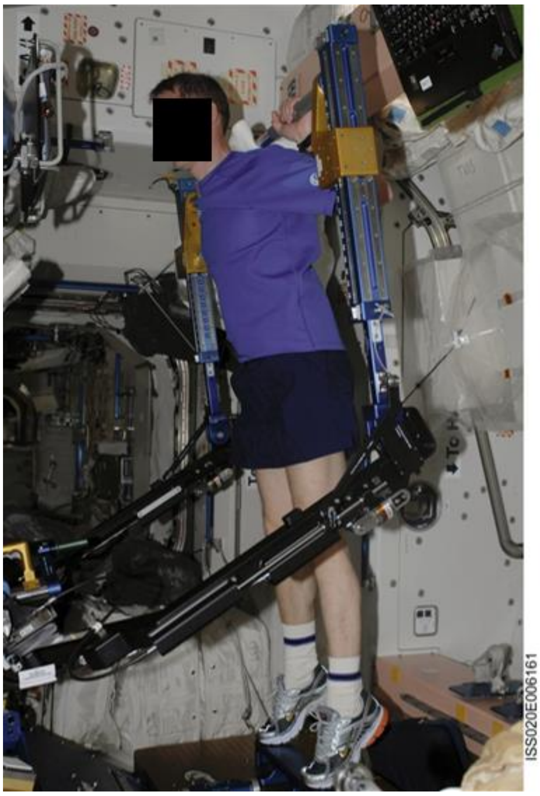

Figure 2. An astronaut performing heel raising exercises on the ARED in microgravity on the International Space Station (ISS). (Photograph courtesy of ESA)

To optimise the positive effects of load on bones and muscles, and minimise stress on joints and passive structures for safety, the physiotherapist works to ensure that the astronaut's spines and legs are in optimal alignment (Figure 3).

Figure 3. An astronaut performing dead lift exercises on the Advanced Resistive Exercise Device (ARED) in microgravity on the International Space Station (ISS). Training feels very different in microgravity, as there is less proprioception and the ARED platform is free moving. (Photograph courtesy of ESA)

To optimise performance and safety, ARED exercises are monitored using real-time feedback via an audio and video conference link with the physiotherapist and sports scientist, located in the EAC in Cologne, they observe the astronaut performing the exercises and provide feedback. If additional feedback is needed, the astronaut can apply Kinesiotape to the lumbar region so they can feel a stretch on the skin if the lumbar spine flexes whilst performing exercises such as squats (Figure 3). A flattened lumbar lordosis is one of the postural adaptations to microgravity. If musculoskeletal injuries occur, the astronaut can contact the physiotherapist through the flight surgeon or by phone, email or direct video/audio conference.

2.3 Postflight Reconditioning

Postflight, the intervention and training programme is implemented within 24h of landing. Aims during this phase include preventing short and long-term painful conditions developing (such as LBP); addressing any mission-induced physical health problems; and returning the astronaut to their preflight condition, without risking the development of pain or injuries associated with readaptation and the resumption of loading. Another aim is to prevent the long-term effects of space flight on the neuro-musculoskeletal system, (as far as is possible).

The underlying principles of the ESA Postflight Reconditioning Programme are:

1) Restore postural control, muscle control and muscle balance
2) Use motor learning principles to normalise muscle recruitment strategies
3) Retrain posture and alignment with the line of gravity
4) Provide appropriate facilitatory stimuli at the optimal time
5) Ensure motor control training precedes strength training and loading.
6) Begin strength training and loading after correct postural alignment is regained.

Because of the abrupt reintroduction of gravity, immediate re-adaptation is required Astronauts are healthy individuals who have adapted to a different environment and are not "sick". However, on entering the Earth's atmosphere, their prior adaptation to microgravity predisposes them to a higher risk of pain and musculoskeletal injuries. The reconditioning programme teaches astronauts to move again in normal, complex three-dimensional movement patterns, and includes improving reaction speed and control of fast movements, that are not performed in microgravity.

The timeline of the reconditioning programme involves the astronaut being seen daily for two hours for up to three weeks (Figure 4), with a break over the second weekend. The reconditioning can occur at different locations. If further care from the physiotherapist is required or requested, the programme can be extended.

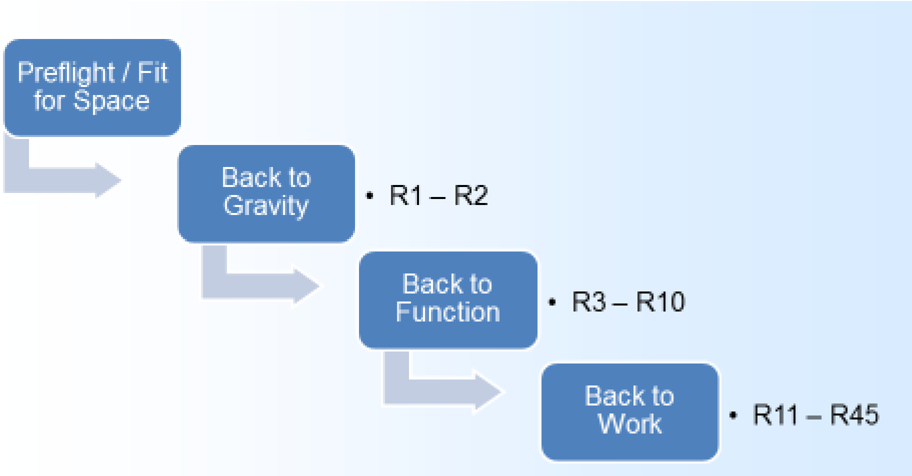

Figure 4: Timeline of the ESA reconditioning programme after long-duration flight. (R+x = Return plus number of days)

2.3.1 Return + 1-2 days (R +1 to R+2).

The astronaut sees the physiotherapist first for a musculoskeletal examination, which includes all spinal and limb joints, potential muscle pain, posture and motor control. The potential use of more structured movement screening in astronauts is discussed by Hides et al (2017). The amount of dysfunction of the vestibular system varies between astronauts and the vestibular system may be acutely affected in the initial stages, causing motion sickness, and balance and gait disturbance (Carpenter et al. 2010), so head rotation may have to be avoided on the first day and carefully increased as the astronaut is able to tolerate.

Assessment and training of the antigravity (or weight-bearing) muscles begin voluntary, isolated contraction of specific muscles, e.g. trunk (abdominal and paraspinal), serratus anterior and vastus medialis are performed. During upper limb movement, the physiotherapist looks for compensation strategies, such as excessive shoulder elevation and alteration of the normal scapulo-humeral rhythm or overarching the lumbar spine.

When re-educating antigravity muscles, the programme always commences with trunk control, to provide a stable base for limb movements. The physiotherapist uses ultrasound imaging and manual assessment to ensure the astronaut is able to activate the deep muscles independently of the superficial muscles (Figure 6). Ultrasound is also used to assess trunk muscle size on R+1, R+8 and R+15. Results of a case history from an ESA astronaut showed that the multifidus muscles were decreased on R+1, especially at the L5 vertebral level and thickness of the internal oblique muscles increased. Motor control retraining restored the preflight size and function of these muscles by R+15 days (Hides et al 2016a). During postural training, recruitment of antigravity muscles must be integrated with the whole muscle system. It is important to note that the astronaut predominantly works in the sagittal plane in space. In postflight reconditioning, it is important to reintroduce movement in three planes. Postural training is progressed from simple to complex movements, later without vision (heavily relied upon in microgravity). Motor control training is essential to restore normal movement patterns and improve proprioception.

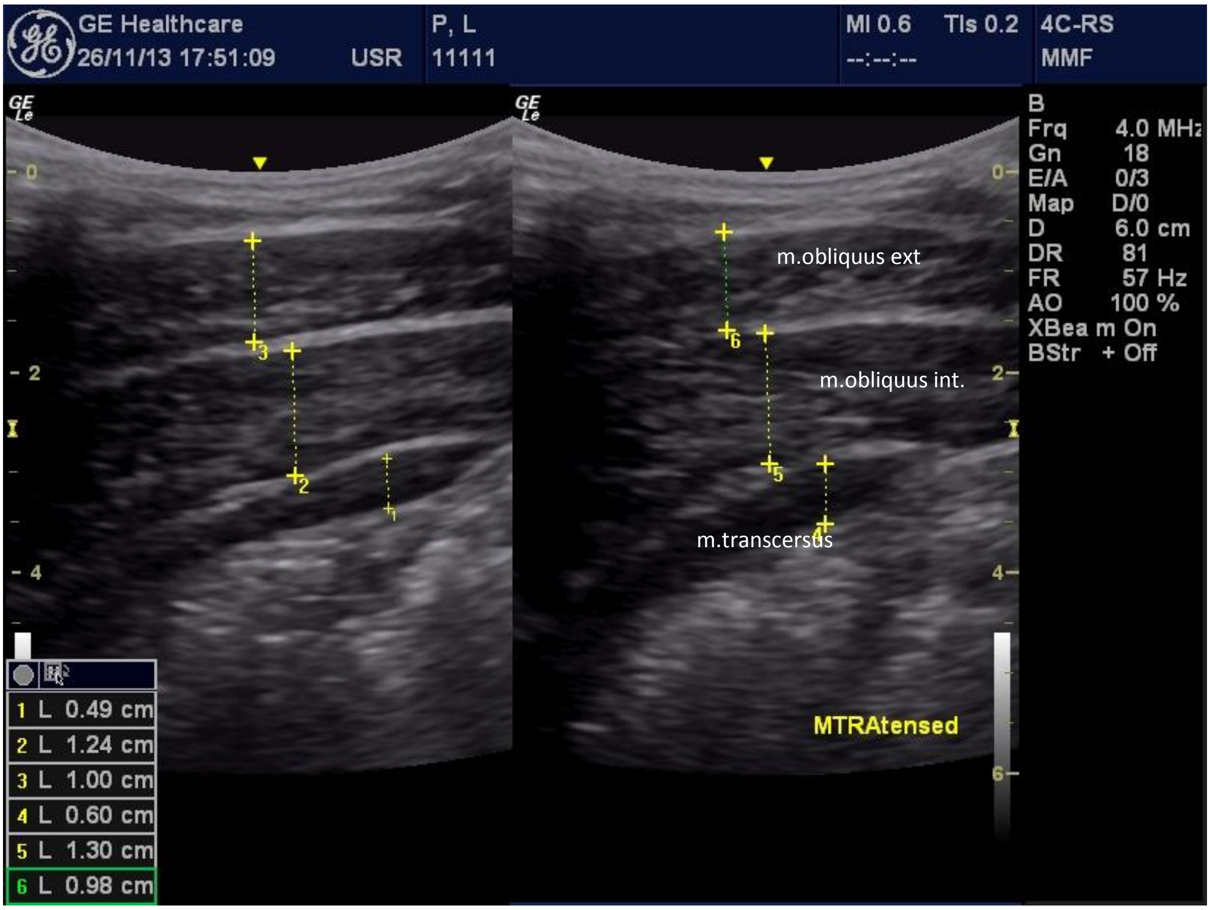

Figure 5: A transverse ultrasound image of the anterolateral abdominal wall using a split screen function. Left image - relaxed state; right image - abdominal wall drawn in, showing increased thickness of transversus abdominis (TrA).

2.3.2 Return + 3-4 days (R+3 – R+4)

The level of difficulty of motor control and postural exercises is increased. A rubber band can be used to increase resistance and compression through the upper limbs, trunk and lower limbs during functional activities, such as sit to stand. Holds in different positions can be used to train endurance.

2.3.3 Return + 4-5 days (R+4 - R+5).

Exercises with the sports scientist are now implemented or earlier (even R+3) if the astronaut is improving rapidly. Exercise in water is a popular activity with astronauts, which gradually increases loading through the joints. In Houston, USA, an underwater treadmill is used. The astronaut then needs to improve their gait pattern on a standard treadmill, adding activities such as cycling and rowing if they wish. Compliance is improved by identifying which exercises the astronaut finds most enjoyable, a topic discussed by McKay and Standridge (2017).

Balance and co-ordination are assessed in exercises such as standing with eyes closed, squatting, single leg stand, moving from half kneeling position to standing, diagonal arm-leg co-ordination and shoulder/hip rotation. Impairments observed are used to inform the level at which the reconditioning programme begins to match the astronaut's ability. The astronaut can progress quite rapidly to whole body exercises if balance and co-ordination are adequate. Any musculoskeletal injuries or painful symptoms are treated with the relevant physiotherapy treatment techniques prior to exercise.

Progression. Motor control training and postural training are the key objectives in the first days of reconditioning. This is necessary to allow progression to weightlifting (strength) and endurance training (see Petersen et al. 2017), carefully monitoring e.g. position of the lumbo-sacral junction during movement. Motor control training is therefore applied to more challenging and functional exercises. If, however, the astronaut is unable to control their spinal alignment during function, they are encouraged to exercise at a lower level where optimal postural alignment can be maintained. Quality of movement is always more important than quantity of movement and / or load. The complete reconditioning programme is shown in Appendix 1.

3. Discussion

Three stages of conditioning and reconditioning during a mission cycle have been discussed in this clinical commentary. Parallels can be drawn between principles of physiotherapy management for people with various conditions on Earth (Hides et al 2016a, 2017; Payne,et al, 2007). However, physiotherapy management of astronauts does present some unique challenges.

As the astronaut's proprioceptive feedback is decreased, the lumbar lordosis is flattened and the discs are hyperhydrated, precise positioning of the spine is challenging. In the absence of being able to correct the position manually, an important feature of the inflight programme is the physiotherapist providing real-time feedback to the astronaut by audio/video conference. The ability to control the position and motion of the trunk over the pelvis is important to allow optimum production, transfer and control of force and motion to the terminal segment (Kibler et al 2006). The correct performance of an exercise is as equally important in microgravity as it is on Earth, particularly to avoid injury when using exercise equipment.

3.1 Parallels with terrestrial populations

Pre-flight training can be likened to pre-season training in elite sport. The goal is to have the athletes in the best possible physical condition in preparation for the competitive season. Some sports (e.g. flexor dominant sports) can induce muscle imbalances (Hides et al 2012), as occurs in astronauts. In addition, muscle size and ratios between muscles have been used to predict injuries in athletic populations (Hides et al 2014, Hides et al 2016b). In footballers, motor control training has been used throughout the playing season and shown to reduce the number of games missed due to injury and to decrease LBP (Hides et al 2012). For astronauts as well as athletes, programmes must be tailored and adjusted to meet functional demands, as well as be appropriate for the age and health of the individual, who may present with a history of pre-existing injuries.

The period of postflight reconditioning parallels many aspects of physiotherapy for people on Earth. One exception is the irritation of the vestibular system of the astronaut in the initial period, which is not common when treating musculoskeletal conditions, although it does occur in neurological conditions. Similarities between astronauts postspace flight and chronic LBP patients include altered posture, altered proprioception and, altered motor control (Bloomberg et al 1997, Mulavara et al 2010) and deconditioning. Assuming poor postures, such as flexed spinal positions in front of computers, induces decreased use of spinal extensor muscles, as seen in astronauts. Thus there are some similarities between the principles used to treat astronauts postflight and chronic LBP patients, who may need to work on motor control (Wood et al 2011), postural control and alignment (Charles et al 2001) and re-establishing good patterns of pain free normal movement. In both conditions, overloading the spine in less than optimal positions can cause injuries.

A major difference between postflight reconditioning and treating people with LBP is the speed of recovery. Astronauts are generally reconditioned much faster than patients with chronic LBP, probably because pathology is not present in the majority of cases. However, researching astronauts can provide direct benefits to terrestrial LBP patients. Although LBP can take many years to develop on Earth, astronauts develop neuromuscular features similar to some of those exhibited by people with LBP in a very short time. The pattern of changes in the musculoskeletal system is predictable. Studying astronauts allows measurements and interventions to be trialled before, during and after exposure to microgravity. Parallels with deconditioning in areas of terrestrial rehabilitation, such as sports injuries, neurological disorders and intensive care, are discussed by Hides et al (2017). Possible solutions to the challenges of conducting research in postflight reconditioning are discussed by Beard and Cook (2017).

3.2 The future

Exploration missions of up to two years, such as to Mars, will involve astronauts undertaking expeditions on the planet surface. This will not only require finding effective ways to maintain compliance with inflight exercise over a longer time but also developing preconditioning exercise programmes specifically to prepare the astronaut for working in a novel gravity environment on another planet (Stokes et al., 2017). A particular challenge will be that preconditioning will not benefit from direct feedback by specialists on Earth, since live video link may not be possible.

4. Conclusion

The ESA programme uses the best evidence available to provide the astronaut with exercise programmes to prepare for a mission (preconditioning), limit the effects of microgra vity during a mission (countermeasures) and postflight retraining to enable safe and rapid recovery (reconditioning). Multiagency collaborative research would provide the opportunity to develop and evaluate the optimal programmes for the unique challenges ahead for astronauts undertaking extended duration missions.

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Appendix 1.

Table 1: **The ESA Reconditioning Programme Schedule, including objectives, exercise types (with examples), intensity and volume of exercises performed by the physiotherapist and exercise scientist with astronauts following space flight.**

Time period (Phase/R+)	**Objective(s)**	**Exercise Type/Method**	**Example**	**Intensity**	**Volume**
Phase 1					
R+1	Physiotherapy: -status quo Training of multifidus and m transversus -Check posture, tonus, tension, mobility -Diagnostics (Ultra Sound) -Reorganization of stabilizing chain -Posture correction -Tonus normalization -Muscle balance -Active postural control	MCE (Motor control exercise) Isolated exercises for m multifidus and m transversus abdominis Exercises for all stabilizer muscles Closed chain exercises Axial training Massage	Prone position: breath in and out with isolated/segmental activation of multifidus (hand feedback), Supine position: draw-in belly button Trunk exercises	Low	90 min
R+2	-Progression on R+1 exercise -Isolated training of stabilizers	MCE with rotational elements: Axial training	Kneeling: rotate basketball (upper body rotation)	Low	90 min

	-Integration of stabilizing muscle system into complete muscle corset -Muscle balance -Active postural control	Upright position (sitting, standing) Individual physiotherapy treatments Closed chain exercises	Sitting: lift med ball towards ceiling Trunk and arm exercises Rotational exercises Session with sport exercise specialist		
R+3	-Progression from R+1 exercise -Isolated training of stabilizers -Integration of stabilizing muscle system into complete muscle corset -Muscle balance -Active postural control	MCE with rotational elements: Axial training Balance training Coordination training Increasing movement velocity (w increased stability of CM) Training of shoulder axis	Standing: rotate ball side to side Trunk, arm and leg exercises Walking on unstable underground Decrease of base of support Sport exercise session	Low	90 min
R+5	-Integration of postural control into more complex exercises -Increased demand and complexity of movement -Approximation to functional exercise movements	Manual therapy Fascial training Low intensity functional exercises Balance/Coordination training Local muscular endurance	Flexibar exercise on balance board Physical exercise session Endurance training with reduced body weight (pool, Alter-G), Resistance training (low loading, controlled motion –	Low	90 min

		Whole body loading Stretching Closed eyes exercises (MCE)	continued supervision of posture by coach) Trunk rotation movements (e.g. such as in Tai Chi)		
R+7	-Integration of postural control into more complex exercises -Increased demand and complexity of movement -Approximation to functional exercise movements -Increase of complexity and intensity	Manual therapy Fascial training Reaction training Core stabilization Balance/Coordination training Local muscular endurance Whole body loading Stretching	Complex coordinative ball handling exercises Initiation of combination moves Squats with low loads and (supervised) focus on form	Low-medium	90 min
R+10	-Increased complexity and intensity of preceding exercises	Same as before -Continued integration of physiotherapy exercise preparations into exercise programme -Motion control in exercise movements	Physical exercise session Complex combination of forward steps, balance movements and sudden stops	Low-medium	

R+11	-Based on previous results, increased integration of functional exercises/movements -Increased complexity -Increased intensity	Same as stated above/before and additionally -Integration of reactive/eccentric exercises	Physical exercise session Complex combinations of forward steps, balance movements and sudden stops (movement control throughout entire motion) Plank exercises Push-ups on gym ball (core strength). Hopping exercises with coordination ladder, steps Rowing (Endurance training) Stretching	Medium	90 min
R+13	-Based previous results, increased integration of functional exercises/movements -Increased complexity -Increased intensity -Construction of “target movements”	Same as before and -Agility -Extended 3D-spatial orientation (+management of additional tools: ball)	Physical exercise session Combination of jumping and throwing Moving in larger radius Parcours (combine moving and tasks) Circle training (endurance, coordination)	Medium	90 min

R+15	-Based on previous results, increased integration of functional exercises/movements -Increased complexity -Increased intensity -Construction of "target movements"	-Coordination and endurance -Construct target final movement (isolated elements) -Training of muscular strength (incl. stability) -Endurance -Agility -Plyometric basics -	Physical exercise session Coordination and endurance Ball dribbling (varied situations with partner) Resistance exercises: Squat, Back extensions/deadlift, Hopping exercises (plyometric training prep/controlled) Parkour	Medium	90 min
R+18	-Integration of optimized posture and movement strategies into more complex functional (athletic and daily life) motion -Posture protection & -Movement safety -Continued body loading	-Training of elements of more complex movements with many repetitions (eye-hand coordination, distracted attention (2 simultaneous tasks) -Training of muscular strength (incl. stability) – progressing intensity -Endurance -Agility	-Step-ups with passing/catching/ throwing a ball, -Work on constructing elements of more complex movements into one -Loaded squats/deadlifts/seated row	Medium	90 min
R+21	-Achieve target exercises/final target movement performance (complex combination with basketball) -Successful and complete integration of postural optimization into functional movement -Bone loading	Athletic movements from ball/game sports, resistance & strength training, Pilates, Martial arts fitness,	Target exercise movements/positions: -Basketball dribble and shot -Balance complex position (Tai Chi/Yoga) (Standwaage)	Medium-high (in complexity, not yet extensive loading)	90 min

	-Achieving complex balance/movement stability -Enable crew to return to complex and intense physical exercise and - “Crew physical functional empowerment” -Undertake a “normal” pre-flight exercise programme	Endurance (Running, Cycling, Swimming, …), Plyometric exercises (controlled)	-Work/Life: lift & carry (heavy) load -Sports: MMA CrossFit” /functional fitness movement variations -Sports: Pilates/Yoga -Sports: Climbing (if possible)	Significant for endurance and strength training Control of movement over intensity (priority)	