Chapter

# GRIP: Dexterous Manipulation of Objects in Weightlessness

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## Abstract

The aim of the GRIP experiment is to investigate how gravity impacts the kinematics and dynamics of the upper limb during dexterous manipulation of objects and how the central nervous system adapts to long-term exposure to microgravity and subsequently back to Earth gravity. Hence, we proposed to conduct a set of experiments on healthy human subjects, involving the manipulation of an instrumented object during exposure to normal and microgravity, and to study how the central nervous system adapts motor control in order to cope with the new physical environment. More particularly, the coordination between the grasping force (or grip force, GF) and the load force (LF) is studied, as well as the adaptation of the movement dynamics and kinematics and the interaction between cognitive and sensory cues that establish a reference frame for the human brain. Here we describe the background motivation, the parabolic flight tests that initiated the scientific hypotheses and the technical and scientific process that led to the implementation of the GRIP experiment currently on board the International Space Station (ISS).

**Keywords:** manipulation, grip, weightlessness, gravity, force, kinematics, space, cognitive, human, brain

## 1. Introduction

### 1.1 Project background

A stable grip on handheld objects is of primary importance to lifting and moving actions particularly when such objects are used as tools. During object manipulation, predicting the consequences of one's own movements is necessary to avoid unwittingly dropping the object. Studies of the forces employed in the dexterous handling of objects have found that the grip forces are tuned to prevent accidental slips and yet are not so excessive as to crush a fragile object or to cause muscle fatigue [1]. Flanagan and Wing [2, 3] examined grip force modulation as subjects performed either point-to-point or cyclic arm movements with a handheld load. They found that variations in inertial forces caused by the subjects' own arm movements over a range of accelerations produced synchronous changes in grip forces that rose and fell with the changes in the tangential load forces on the fingers while also taking into account the friction between the fingers and the object. A tight temporal coupling between the grip force (GF) and the load force (LF) has been documented in a large variety of tasks engaging different kinds of objects, grips, loads or mode of transport and locomotion. In other words, grip forces were controlled in anticipation of the fluctuations in inertial forces.

Changes in gravity can be considered as major perturbation for these tasks, which must be handled by the motor system. This is particularly a challenge for loads applied by gravity to the body because the muscle activities used to compensate these loads appear to be programmed in a highly predictive manner, probably based on a lifetime experience in a normal 1 g environment. It has been shown that during exposure to microgravity in parabolic flights, the control of interaction forces adapts at least partially to the lack of gravity [4–9], yet evidence indicates that anticipation of gravity's effects persists in the short term and that adaptation is not fully complete [10–12]. The motivation for the GRIP experiment, to be performed in long-duration space flight, is to understand how the central nervous system adapts to an environment without gravity's effects and what will be the consequences of long-term adaptation when an individual returns to a normal (Earth) or partial (Moon or Mars) gravitational field.

### 1.2 Hypothesis

We hypothesized that the central nervous system anticipates the effects of gravity in a normal Earth environment but that after long-term exposure to 0 g, grip force/load force coordination and control of upper limb trajectories will adapt to the particularities of the 0 g environment by means of re-optimization of the motor control policy.

### 1.3 Research objectives

The experiment described here targets specific questions about the effects of gravity on dexterous manipulation, questions that cannot be addressed in the normal terrestrial environment. The research carried out in this project contribute to our understanding of how the human nervous system controls movement both on the ground and in the microgravity environment of spaceflight. Data from these experiments may also be used to identify potential hazards for astronauts as they move between different gravitational environments. These studies could also contribute to the design and control of intelligent haptic interfaces to be used in challenging environments such as space.

More specifically, GRIP addresses the following questions:

- Can the central nervous system dissociate static (due to gravity) and inertial (due to acceleration) loads in the control of precision grip?

- Is grip force control for the manipulation of objects more sensitive to the friction between the fingers and the object in microgravity?

- Do up/down asymmetries observed in dynamics of precision grip and kinematics of the upper limb disappear during long-term exposure to microgravity?

- What visual and kinaesthetic cues are used by the central nervous system to establish an "up and down" reference frame for the control of limb trajectories and applied forces in the absence of gravity effects?

- How does grip force/load force coordination evolve during long-term exposure to microgravity?

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- What after-effects influence grip force control on return to a gravity environment?
- Does the learning of kinematics parallel the learning of dynamics in microgravity?
- How does gravity alter decisional processes as measured through the reaction time during fast upper limb movement?

## 2. Preparation of grip during parabolic flights

Our first parabolic flight campaign participation was during the 26th campaign organized by the European Space Agency (ESA) that took place in Merignac (France) in 1999. Then between 1999 and 2014, we participated in 21 parabolic flight campaigns. This allowed us to properly prepare our GRIP experiment before launching it to the ISS. During this preparation period, the GRIP project allowed us to train 11 PhD students and publish 32 scientific papers. We present hereafter as examples some interesting results of these experiments in parabolic flights.

### 2.1 Gravity influences the rhythm of our movements

We investigated humans' ability to sustain rhythmic movements in different gravity environments [13]. By analogy with a simple pendulum system, the self-generated pace should grow as a function of gravity. However, because the natural period would be infinite in 0 g, this simplistic model fails in microgravity. Therefore, we hypothesized that the movements are partly driven by a central pattern generator (CPG) in a closed loop with the arm. Since neuronal control systems cooperate with the physical constraints imposed by the dynamics of the body and the environment, we expected that a change of gravity would induce a change of frequency to perform efficient rhythmic movements that have adapted to the resonant frequency as a result of gravity level changes. Since there is no resonant frequency in 0 g, however, we predicted that the pace adopted by the participants would rely mainly on the intrinsic frequency of the neural oscillator.

Twelve right-handed volunteers participated in the study. Subjects were successively confronted with periods of normal gravity (1 g), hypergravity (1.8 g) and microgravity (0 g) during parabolic flights. They were instructed to perform rhythmic arm movements with a handheld object of approximately 200 g mass around two virtual obstacles situated 3 m in front of them, following an "infinity-sign-shaped" trajectory. The first group of six participants (self-paced) were instructed to perform the movement at a self-generated pace. The second group of six volunteers (metronome-paced) followed the rhythm dictated by a metronome (one cycle every 1.5 s) (**Figure 1**).

We showed that the frequency of a rhythmic movement of the upper limb was systematically influenced by the different gravity conditions created in parabolic flights. The period of the arm movement shortened with increasing gravity levels. In weightlessness, however, the period was more dependent on instructions given to the participants, suggesting a decreased influence of resonant frequency. Our results are in agreement with a computational model of a CPG coupled to a simple pendulum exposed to gravity. We demonstrated that the innate modulation of rhythmic movements by CPGs is highly flexible across different gravity contexts. This further supports the involvement of CPG mechanisms in the achievement of efficient rhythmic arm movements. Our contribution is of major interest for the study of human rhythmic activities, both in a normal Earth environment and during microgravity conditions in space.

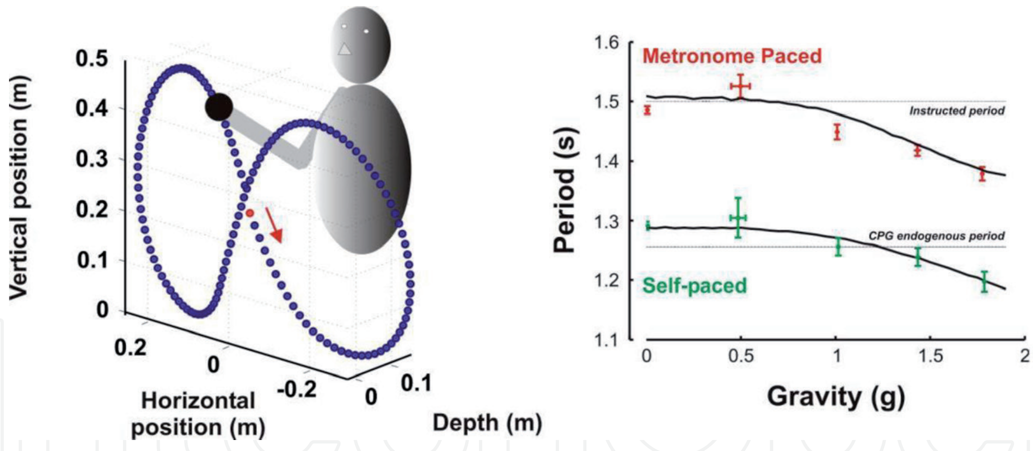


**Figure 1.**
*(Left) One typical cycle trial of a participant in 0 g. The blue dots represent the object position sampled every 10 ms. The arrow marks the path to follow. (Right) Period as a function of gravity: experimental (points) and simulation (lines) data. The data points are the mean periods adopted by the participants in the self-paced group (green) and in the metronome-paced group (red). The bottom dotted line indicates the central pattern generator endogenous period (1.25 s). The top dotted line indicates the instructed rhythm for the metronome-paced group (1.5 s). Self-paced and metronome-paced data were fitted by the CPG pendulum model (solid lines). Error bars represent 95% confidence intervals on both axes (adapted from Ref. [13]).*

### 2.2 Gravity influences the kinematics of our movements

In another study [14], we investigated the effect of hypergravity induced by parabolic flights on the trajectory of vertical pointing movements to test the hypothesis that motor commands are optimized with respect to the effect of gravity on the limb. The subjects sat in front of three visual targets that were aligned vertically with respect to the aircraft floor and that were separated by 18 cm. The centre target was in front of the subject's shoulder and defined the horizontal arm position. They were asked to grasp a manipulandum (mass 250 g, grip aperture 4.5 cm) with the right hand and to perform visually guided pointing movements toward the current target with arm-straight rotations around the shoulder. Upward movements (from the centre to the top) and downward movements (from the centre to the bottom) were randomly interleaved to avoid anticipatory movements. All subjects performed control experiments in normal gravity conditions (1 g) prior to the in-flight experiment. The subjects performed the task during the 0 g and subsequent 1.8 g phases of each parabola (they did not perform the task under normal gravity conditions during the flight). Each subject performed from 60 to 80 trials in each direction and in each gravity condition. The analysis reported in **Figure 2** focuses on the data acquired during the hypergravity phases.

First, the simulations in normal gravity reproduced the asymmetry in the velocity profiles (the velocity reaches its maximum before half of the movement duration), which typically characterizes the vertical pointing movements performed on Earth, whereas the horizontal movements present symmetrical velocity profiles. Second, according to the simulations, the optimal trajectory in hypergravity should present an increase in the peak acceleration and peak velocity despite the increase in the arm weight. In agreement with these predictions, the subjects performed faster movements in hypergravity with significant increases in the peak acceleration and peak velocity, which were accompanied by a significant decrease in the movement duration. This suggests that movement

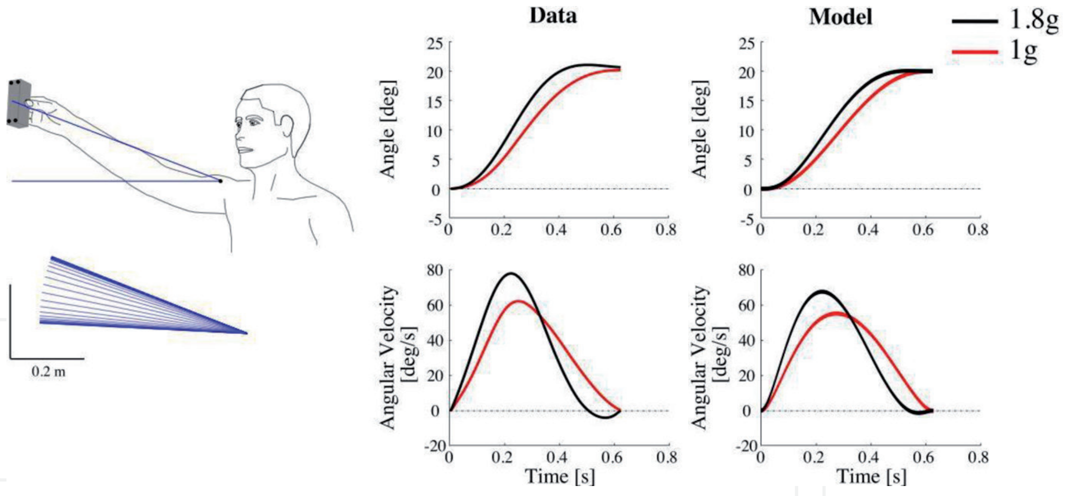


**Figure 2.**
*(Left) Illustration of a subject performing the task. (Right) Trajectories and angular velocity as a function of time in normal gravity (red) and hypergravity (black) conditions for upward movements. Experimental data (left) and model simulations data (right) (adapted from Ref. [14]).*

kinematics change in response to an increase in gravity, which is consistent with the hypothesis that motor commands are optimized and the action of gravity on the limb is taken into account. These results provide evidence for an internal representation of gravity in the central planning process and further suggest that an adaptation to altered dynamics can be understood as a reoptimization process.

### 2.3 Gravity influences the dynamics of our grip

Grip force-load force coordination was studied during cyclic vertical arm movements with a handheld instrumented load across different gravity conditions (0, 1, 1.8 g) induced by parabolic flight maneuvers [4].

Eight adult subjects (including two women) participated in the study. Four subjects had no previous experience in microgravity (the non-experienced subjects, NES), whereas the other four had more than 100 parabolas each to their credit (the experienced subjects, ES).

The results showed that the grip force was modulated in parallel with the load force fluctuations due to the arm movements, regardless of the gravity condition. At new gravity levels, the phase shift between the grip force and the load force was equivalent to that observed in 1 g, even on the first trials of the non-experienced subject. By contrast, the level of the grip force modulation was dependent upon the gravity level, and its adjustment seemed to require some adaptation for the non-experienced subjects. This is illustrated by the more variable grip force-load force coordination in the phase diagrams of the first parabola for non-experienced subjects (see P1 in **Figure 3**). The experienced subjects (ES) adjusted the level of the grip force modulation to the new gravity level as soon as they executed the task in the aircraft. The non-experienced subjects had some difficulty in maintaining the imposed movement and applied unnecessarily high safety margins in their grip force during their first trials at 0 and 1.8 g. In the subsequent trials, they progressively decreased their grip force, and no further evolution in the grip force-load force coupling was seen after the fifth parabola (see P5 in **Figure 3**).

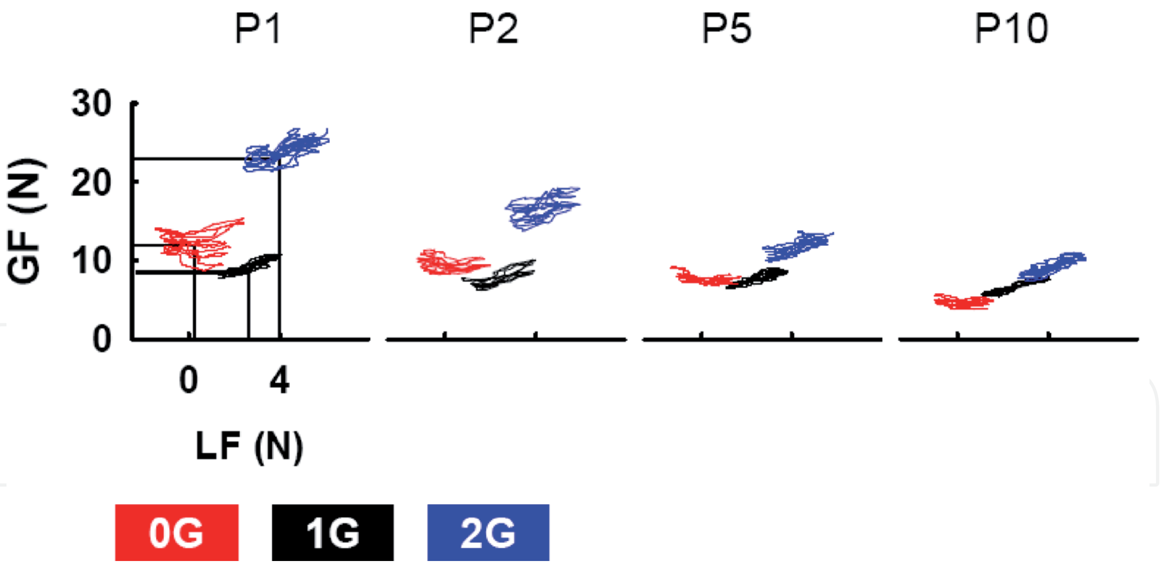


**Figure 3.**
*Phase diagrams illustrating grip force-load force (GF-LF) coordination during vertical cyclic arm movements for non-experienced subject (NES). By decreasing both the level of GF and the variance of GF-LF coordination throughout the 10 parabolas (from P1 to P10), non-experienced subjects progressively tend toward a single GF-LF relationship across the different gravity levels. Identical load force ranges were obtained by varying separately the weight and inertial components of the load force across three different gravity levels (red, 0 g; black, 1 g; and blue, 2 g), and the same coupling GF-LF was observed after the fifth parabola (P5) (adapted from Ref. [4]).*

## 2.4 Restraint system preliminary tests in parabolic flights

Weightlessness is a specific environment where minor limb movements may result in other parasitic body movements. In order to avoid such parasitic body movements when performing the arm movements for the GRIP experiments, the subject will have to be adequately restrained. Indeed, the restraint system will have to maximize the freedom of arm movements while minimizing the trunk, pelvis and legs movements. At the same time, the restraint system must be comfortable, allow a quick egress in case of emergency and avoid inducing pain. During the 53rd ESA parabolic flight campaign of October 2010, different concepts of restraint system were tested, and the subjective perception was recorded for various subjects (see **Figure 4**). The different


**Figure 4.**
*Test of the GRIP restraint system using a GRIP mock-up chair during the 53rd ESA parabolic flight campaign of October 2010 (photo: ESA).*

concepts were tested for the sitting and supine posture, for different arm movements (vertical and horizontal oscillations and vertical collisions) and for different feet positions. It has been shown that the pelvis restraint was strongly recommended and that shoulder straps were important. The main observation was that the weightlessness environment provided by the parabolic flights was required to allow evaluating the impact of the parasitic movements on the subject stability.

## 3. Technical development of grip prior to the launch to the ISS

Before launching any equipment to the International Space Station (ISS), it must follow a technical development answering several categories of stringent requirements regarding mass, size, used materials, electrical design, power consumption, electromagnetic compatibility, structural integrity, fracture control, overall safety of utilization, human interfaces, etc. for ground usage, for interfacing with the launch vehicle, for transfer phases and for final utilization on the ISS. It is a long but essential process to send a scientific experiment in space.

The industrial consortium was chosen after a phase of tendering. The prime contractor was Qinetiq Space nv (previously known as Verhaert D.D.) from Kruibeke, Belgium, with Arsalis, a spin-off of the University of Louvain in Belgium, as main subcontractor in charge of the manipulandum design and electronics. Charnwood Dynamics, from the United Kingdom, was a main supplier of the CODA motion visualization system.

The technical development approach decided to design, develop, build and test the GRIP instrument was what is called the *prototype* approach in which two models are developed. The first model is called the Engineering Model and serves as the main development model. The second is called the Flight Model and is developed after the Engineering Model to be the unit that will eventually fly in space. It was also decided to combine the two initial design phases A and B into a single-phase A/B and the last two technical development and test phases C and D into a single-phase C/D. Due to delays in the definition of some interfaces, it was decided to add an intermediate bridging phase between the end of the Phase A/B and the beginning of the Phase C/D.

Phase A/B was devoted to first, the detailed definition of the scientific requirements of the GRIP experiment and their translation into technical requirements; second, a conceptual design definition where several solutions were proposed by the industrial team and discussed with the scientists to come to a commonly agreed concept; and third, a more detailed definition to bring the chosen concept to a more evolved design with definition of dimensions, subsystems and overall masses, power and interfaces estimations, etc. This Phase A/B was initiated in May 2009 and lasted until March 2010. During this phase, several project reviews and subsystems reviews took place. This Phase A/B culminated in a major review, called the preliminary design review (PDR), whose goal was to finally agree on a detailed design of the GRIP instrument.

In parallel to this design phase, a series of experiments and tests were taking place during parabolic flight campaigns to support the development of concepts and design of some subsystems, like subject restraining straps, supine position support, GRIP chair interfaces etc., as all these “taken-for-granted” design elements that work well on ground in a 1 g environment were not necessarily efficient or optimal in a 0 g environment.

The bridging phase took place from April 2010 till December 2011 and allowed to conduct additional definition tests of various subsystems on ground and during parabolic flights, mainly for the GRIP chair, stretcher, reference frame and manipulandum; requirements for experiment control software were consolidated; the manipulandum was bread boarded for testing its calibration and three-dimensional (3D) tracking accuracy; further bread boarding of printed circuit boards assembly, of the finger humidity sensor and of the lock mechanism was conducted. **Figure 5** summarizes the different steps taken during the Phase A/B and the bridging phase.

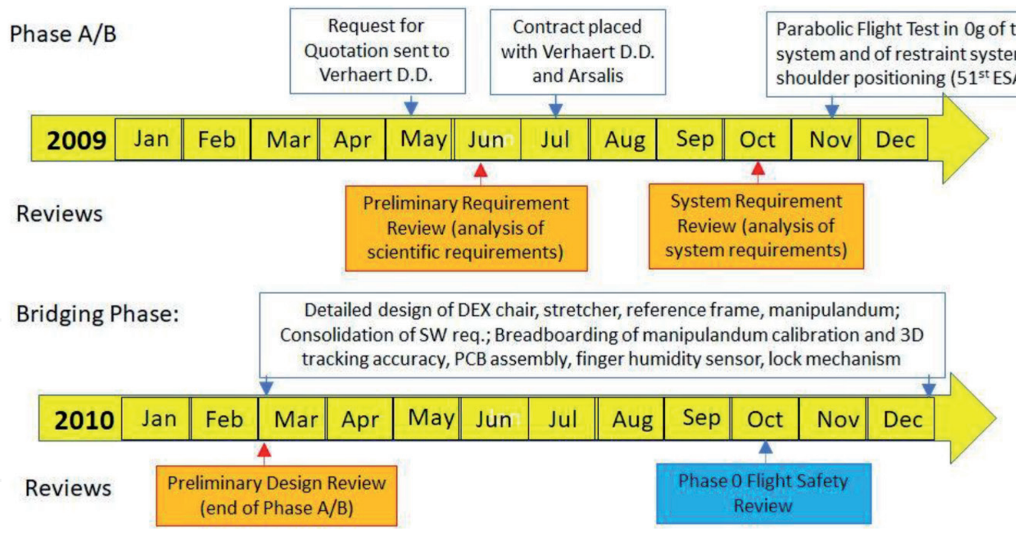


**Figure 5.**
*Timeline of phase A/B and bridging phase (ESA PFC: ESA parabolic flight campaign).*

Phase C/D was aimed at first, completing the definition work to incorporate all the results of separate development and test of GRIP subsystems, in parallel to the development of the GRIP hardware and, second, formally agreeing on the design of each subsystem regarding mechanics, electrical design, electronics, software, etc. through dedicated specific technical reviews. A major change occurred in the middle of the technical development when the launch vehicle was replaced. The initially foreseen vehicles (ESA's Automated Transfer Vehicle and Russian Progress cargo) were replaced by newly available launch vehicles (Orbital Cygnus and SpaceX Dragon) resulting in a formal Contract Change Notice that yielded a major verification of structural load requirements and test programme definition. The part of the Phase C/D that corresponds to the classical Phase C ended with a major design review, called the critical design review, during which the final design was agreed upon and frozen, i.e. changes after this review would no longer be possible or would cost a lot of efforts and could result in a non-readiness for launch. This CDR lasted 4 months and ended in September 2012, with a view to a launch in October 2014 (**Figure 6**).

The part corresponding to a normal Phase D, i.e. the final building, assembly and testing was then formally initiated (although it is commonly a good practice to anticipate the parts procurement, assembly and building). In parallel to technical procurement and development, several reviews took place, not only for technical aspects but also safety reviews and crew reviews (**Figure 7**).

In addition to the Engineering and Flight Models' development, additional Science Models and Training Models had to be built to support on one hand the development of all scientific protocols for the experiment execution with the ground support centre and, on the other hand, to allow the astronaut trainers at the European Astronaut Centre to develop and validate crew procedures before experiments could be conducted on board the ISS. The Phase C/D ended after all tests were successfully completed, at the final Flight Acceptance Review in August 2014, and the Flight Model was delivered for launch vehicle integration. In total, 18 project reviews and four safety reviews were conducted during the technical development Phases A/B and C/D. It was essential to have a good and regular communication between the scientific and engineering teams, to conduct preliminary scientific and technical tests in 0 g during parabolic flights and to be supported by the various space agencies (ESA, CNES, NASA) and the Belgian Science Policy Office.

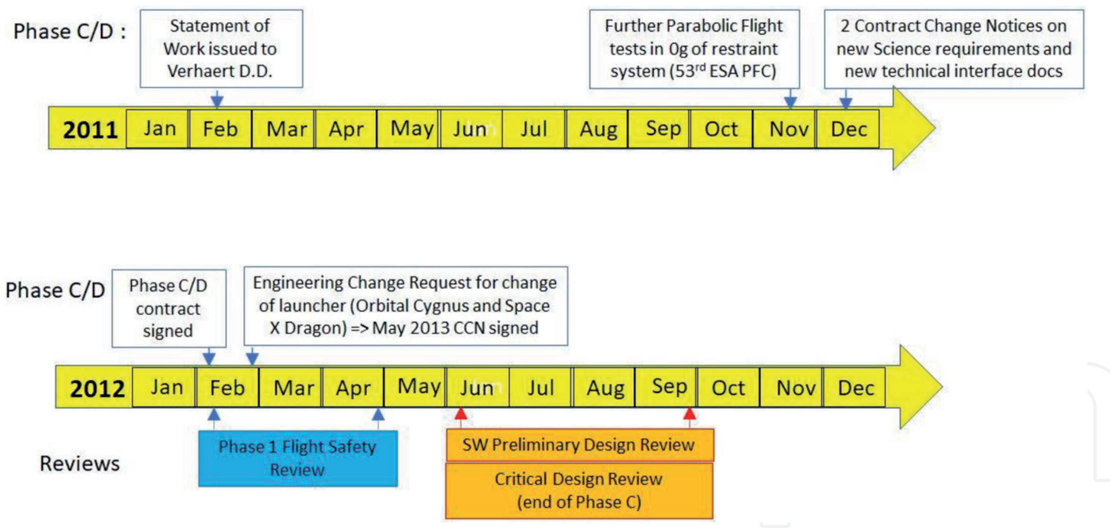


**Figure 6.**
*Timeline of phase C/D until CDR (ESA PFC: ESA parabolic flight campaign).*

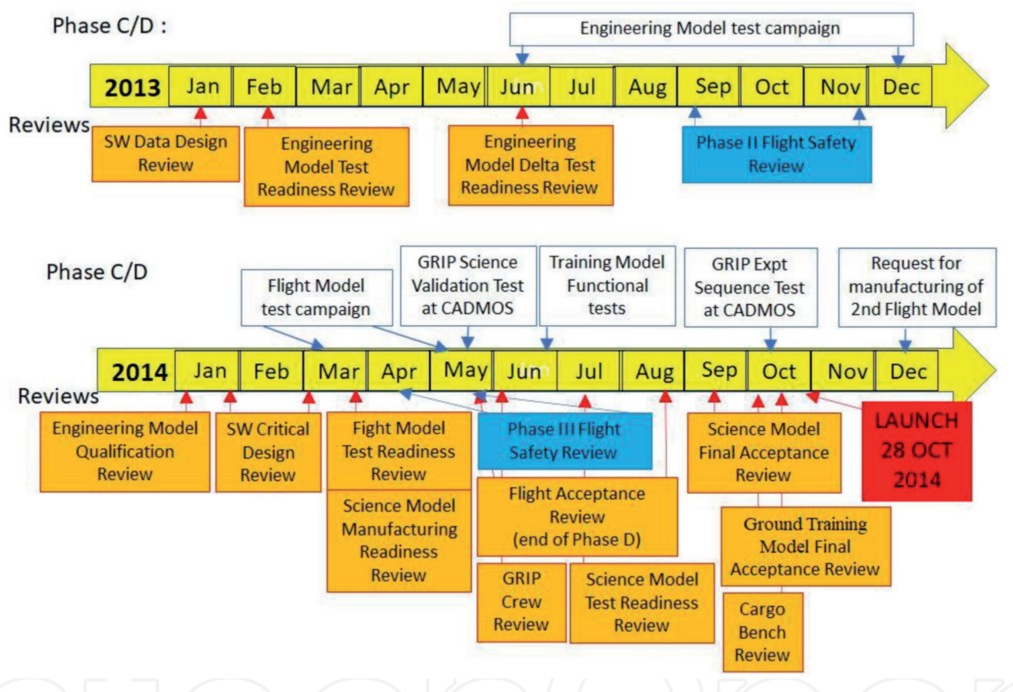


**Figure 7.**
*Timeline of phase C/D from CDR until first launch.*

## 4. Grip instrumentation

The equipment is similar for pre-, in- and postflight sessions. Four similar models (see **Figure 8**) of the GRIP equipment exist: the Engineering Model (for sessions performed in the European Astronaut Centre, Cologne), the Science Model (for sessions performed at the Johnson Space Centre, Houston), the Ground Model (for testing sessions performed at the CADMOS) and the Flight Model (for in-flight sessions performed on-board the ISS).

All models are similar and are equipped with the same hardware items listed below:

**The chair box** (see **Figure 8**) acts as a transport box and as a restraint system when performing the experiment in the sitting position. The chair box accommodates back and foot support, restraint belts, the manipulandum and wrist box,

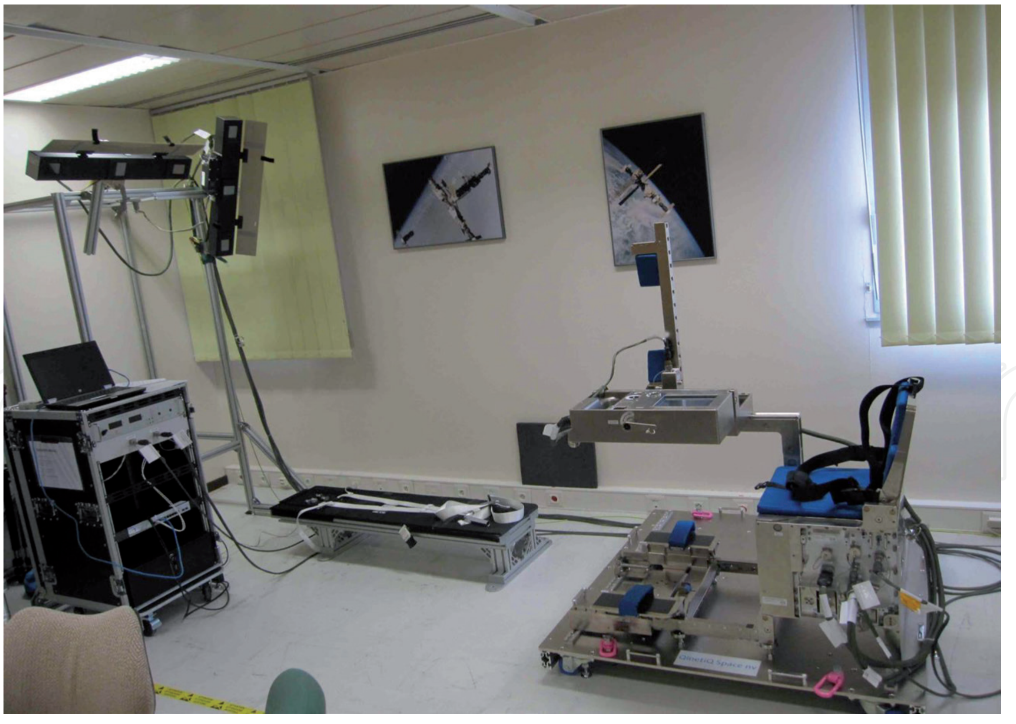

**Figure 8.**
*The GRIP set-up in the seated configuration.*

electronics unit for power, data interfaces and signal conditioning, mounting interface for the reference frame, laptop and headphone.

**The manipulandum** (**Figure 9**) is an instrumented device that can be held in a precision grip between the thumb and index finger. The manipulandum comprises force and torques sensors, accelerometers, gyroscopes and two moisture sensors. Force sensors in the device measure six-dimensional interaction forces and torques between the thumb and the object and between the index finger and the object. Accelerometers in the object are used to measure three-dimensional acceleration. Surfaces under the fingers are equipped with sensors to measure skin moisture. The object is equipped with infrared light-emitting diode (LED) markers to allow for the measurement of the 3D movement by the CODA tracking system (see CODA tracking system below). Additional weights can be added to the manipulandum to change its mass. A system is implemented to provide for a test of the coefficient of friction of the contact between the fingertips and the manipulandum.

**The wrist box** (see **Figure 9**) accommodates eight additional infrared LED markers (see CODA tracking system below). The wrist box is attached to the wrist of the subject in order to track the movement of the arm.

**The CODA tracking system** (**Figure 10**) consists of two motion-tracking units (CODA units, Charnwood Dynamics Ltd.). Each unit encompasses three cameras. These cameras are able to track the position of infrared LED markers placed on the manipulandum and on the wrist box. Each unit can then reconstruct the 3D position of each marker by triangulation. The CODA system is therefore used to measure the movement of the hand and object in 3D space. One unit is equipped with an additional webcam assembly.

**The reference frame** (**Figure 11**) is a mechanical frame that includes the following:

1. The target frame that provides the upper and lower tapping surfaces and the target LEDs that are illuminated under automatic control to define the target position for point-to-point movements. The target frame also accommodates two CODA markers for the spatial reference frame.

2. The utility box that consists of a cover with audio generator, touchscreen user interface, electronics and fan and a cradle for the manipulandum retainer and the additional masses. It accommodates two CODA markers for the spatial reference frame as well. It includes control computer and associated electronics to automatically run the experiment (provide instructions to the subject, generate sequence of targets) and to measure and store data.

The GRIP set-up can be reconfigured to perform the experiment in supine position. In that case, the back support of the chair box is folded, the reference frame position is changed, and the subject lies on a bed equipped with restraint belts.

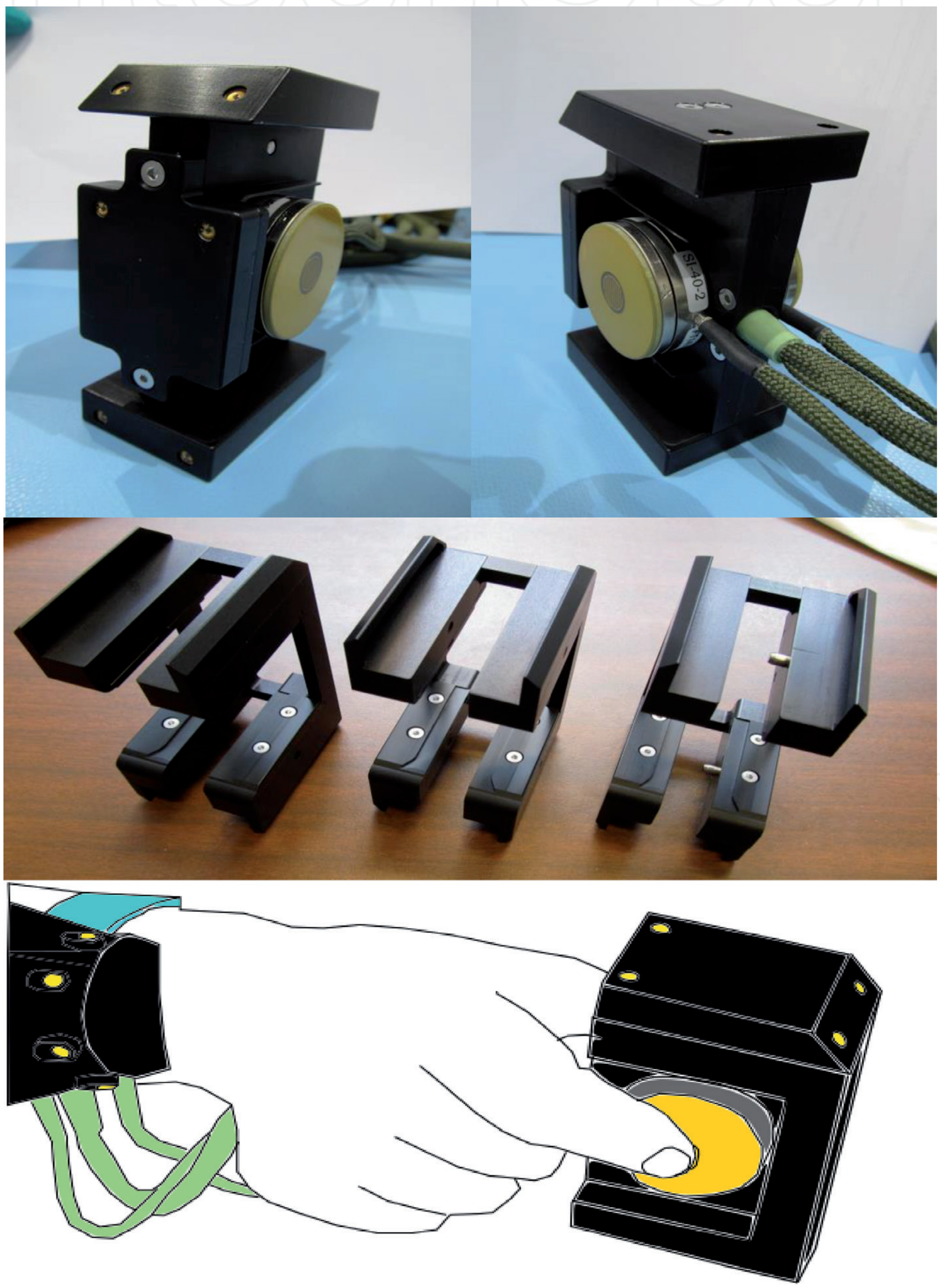

**Figure 9.**
*The manipulandum (top), the additional masses (middle) and the wrist box (bottom).*

**Figure 10.**
*The tracking system (CODA cameras).*

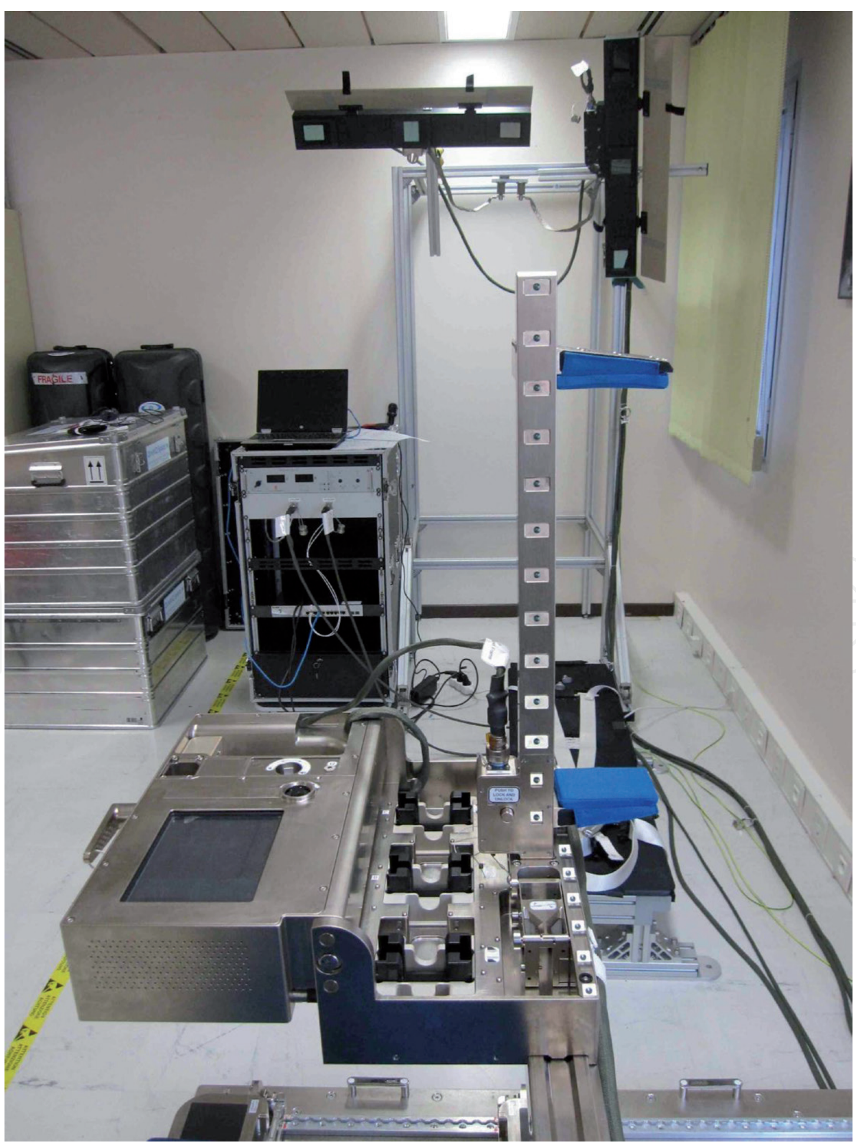


**Figure 11.**
*Astronaut view of the setup in the seated position.*

## 5. Grip in the International Space Station

The launch took place in October 2014, and unfortunately, the rocket exploded a few seconds after take-off (**Figure 12**). It resulted in the complete destruction of the GRIP Flight Model. It was decided very rapidly by the ESA and with the support of the Belgian Science Policy Office to rebuild the GRIP Flight Model during an additional extension phase from December 2014 till 2017.

The second launch took place successfully in February 2017 and the first commissioning of GRIP in May 2017. The first on-board 6-month experiment took place with the first subject in 2018 (**Figure 13**). The second and third subjects successfully performed GRIP experiments on board the ISS in 2019, and two additional subjects are planned in 2020.

During every task of the experiment, the astronaut holds the manipulandum between the thumb and index finger of the right hand. He/she performs a variety of movements (oscillations, point-to-point movements and controlled collisions) while holding the manipulandum in the hand and being either in sitting or supine position. The movements of the manipulandum and of the hand are measured, as well as the forces acting between the fingers and the manipulandum and the moisture of the fingers. A typical full session is broken into three sub-sessions: dynamics seated, references seated and references supine protocols.

**Figure 12.**
*Explosion at launch of the Antares rocket with orbital sciences Cygnus CRS-3 vehicle on 28 October 2014 with the first flight model of the GRIP instrument (credit: NASA).*


**Figure 13.**
*The first on-board 6-month experiment took place with the German ESA astronaut Alexander Gerst in 2018 (credit: ESA/NASA).*

## 5.1 Protocols

### *5.1.1 Dynamics seated protocol*

Participants perform a set of experimental trials in the seated posture.

First, they perform a test of the coefficient of friction. We have developed a simple and reliable method to estimate the coefficient of friction in weightlessness. Our method is based on active, back-and-forth movements of an astronaut's finger on the manipulandum six-axis force sensor. The static coefficient of friction is computed as the ratio of the tangential to the normal force at slip onset. (For more details see Barrea et al. [15]).

Then, they perform oscillatory movements of the arm with three different masses for the manipulandum, at three different frequencies. The sequence of masses and frequencies is instructed by the control computer and may be varied from session to session. Thereafter, the participant performs targeted point-to-point movements to visual targets presented in random order in both the vertical and horizontal directions (see **Figure 14**). At the end of this protocol, they repeat the test of the coefficient of friction.

### *5.1.2 References seated protocol*

Participants perform another set of experimental trials in the seated posture. First, they perform a test of the coefficient of friction. Then, they perform rapid discrete movements between two target positions located along a vertical line with eyes open. After that they perform rapid, discrete movements to the remembered position of the same vertically arranged targets, with eyes closed. Rapid, discrete movements are subsequently

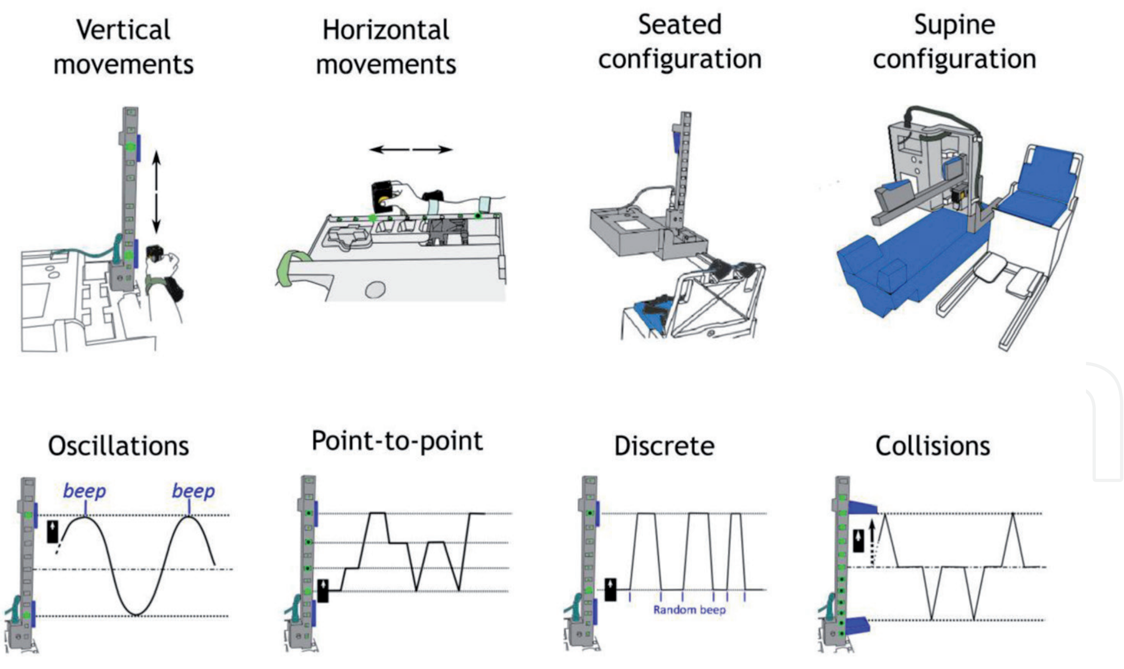


**Figure 14.**
*The astronaut performs a variety of movements (oscillations, point-to-point, discrete movements and controlled collisions) while holding the manipulandum in the hand and being either in sitting or supine position.*

performed with eyes open and with eyes closed, as above, with the targets located along a horizontal line. Finally, participants perform a set of tapping gestures in which the manipulandum is moved rapidly upward or downward to collide with surfaces that are rigidly attached to the target structure (see **Figure 14**). Audible tones are used to indicate to the participant which surface (above or below) must be tapped on each trial, in random order. At the end of this protocol, each participant repeats the test of the coefficient of friction.

### *5.1.3 References supine protocol*

Participants perform the same set of trials as described for the "references seated" protocol, but now in the supine posture (lying down on his/her back).

### *5.1.4 Sensor check*

In addition to the science protocols described above, a "sensor check" protocol has to be performed at least once during each increment for which the GRIP experiment is performed on orbit and shall be performed at least once after the final GRIP test session on orbit. Specific oscillatory movements are performed with the manipulandum in order to verify the integrity of the force sensors and accelerometers. This calibration procedure is performed on both ground and flight equipment to ensure that any differences in measured values between experimental trials performed on the ground and during flight cannot be attributed to differences in the hardware, rather than to differences in sensorimotor processing by the central nervous system in weightless conditions.

### 5.2 Session planning

A full session consists of the dynamics seated, references seated and references supine sub-sessions. There are two preflight Baseline Data Collection (BDC) sessions. BDC1 may be performed any time 360 days prior to launch. BDC2 must be scheduled not more than 180 days prior to launch. There are three reduced postflight sessions lasting 30 min each, in between 1 to 6 days post return on Earth. Additionally, three full postflight sessions are planned: one early session 12 days after return and two late sessions 30 days after return, with a minimum of 1 week between sessions. Pre- and postflight BDC sessions are taking place in Cologne or in Houston.

### 5.3 Commissioning

Before the first in-flight session on-board the ISS, a commissioning session was performed by a surrogate subject in order to verify the equipment integrity. The commissioning included a complete deployment of the equipment, a "sensor check" protocol and a reduced version of the dynamics seated, references seated and references supine protocols.

## 6. Support of ground control centers

The development of the GRIP experiment and its implementation in the ISS would not have been possible without a strong support of experts, which was provided by the CADMOS (*Centre d'Aide au Développement des Activités en Micropesanteur et des Opérations Spatiales*) from the CNES (*Centre National d'Etudes Spatiales*, Toulouse, France). The central role of CADMOS is to help scientists prepare their experiments, to provide support and monitoring and to downlink the data from the ISS. In particular, CADMOS' team provided support for the Scientist Validation Test and the Experiment Test Sequence that were both performed at CADMOS facilities on the ground to test the hardware and the smoothness of the operations and coordinated the Commissioning that was run on-board the ISS by ESA French astronaut Thomas Pesquet to test the equipment. CADMOS also acts as a crucial link between the scientific team and the Columbus Control Centre (COL-CC) which is based in Munich and which controls all experiments performed on-board the Columbus module. CADMOS also coordinates with the European Astronaut Centre in Cologne for the training of the astronauts and can support the scientists during the Baseline Data Collection when it is judged necessary. BDCs performed in Houston are supported by the Johnson Space Centre from NASA.

## 7. Conclusions

The GRIP project investigates object manipulation in microgravity. It is an epic journey to the ISS that is nicely illustrated and motivated in this short (5 min) video [16].

This project required a lot of essential ingredients. Indeed, it relies on excellent scientific competences, an outstanding support from the different agencies (Belspo/Prodex, ESA, NASA, CADMOS) and contractors (QinetiQ, Arsalis). A lot of patience, professionalism and determination were also needed to reach a long-term goal and to overcome many obstacles over more than 20 years. Indeed, GRIP was not even spared a rocket explosion. One of the key elements of this success is the valuable trust among the different partners that was often supported by a true


**Figure 15.**
*The GRIP badge in front of the ISS porthole with the earth in the background (courtesy of Luca Parmitano).*

friendship that built up over the years. This is truly a team work that is a reflection of the immense success of the ISS project built on international collaborations.

The experiments could recently be performed on board the ISS thanks to all the preparatory scientific work of excellent quality conducted by all our PhD students in our laboratories and in parabolic flights. Finally, it is very important to give special thanks to our experimental subjects on board the ISS. Indeed, it is important to stress that we were often stunned by the dedication of all our astronaut subjects who conducted GRIP experiments in conditions that were sometimes difficult.

We are convinced that GRIP experiments will make a very significant contribution to our understanding of dexterous manipulation and adaptation to long-term microgravity. This should also shed some light on motor learning and hopefully guide clinicians who aim at helping patients suffering from motor control pathologies (**Figure 15**).

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