Eye-Hand Coordination: Dexterous Object Manipulation in New Gravity Fields

The stabilisation of an object manipulated with the hand depends on applying a sufficiently strong force with each finger such that sufficient friction is generated to resist the load force acting tangentially to the contact surfaces. Gravity normally provides a constant force acting on the object (depending on its weight) which is adequately taken into account by an appropriate level of grip force. Variations in inertial forces caused by the subject's own arm movements over a range of accelerations also produce synchronous changes in grip forces that rise and fall with the changes in the tangential load forces on the fingers. That is, grip force reflects an anticipatory adjustment to the fluctuations in inertial forces. The modulation of grip force in anticipation of load force implies that the nervous system has access to information concerning the object's weight, mass and the kinematics of the forthcoming movement, since changes in any of these require a different grip force. This suggests that the internal models used to predict load forces and generate appropriate grip forces are pretty good. It remains to be proved, however, whether the entire control process of grip-force compensation is based on feedforward, model-based control, or if some components of the required grip responses are generated through reflex actions.

Microgravity presents a significant challenge to dexterous object manipulation for a number of reasons. Owing to all the potential deviations from the expected characteristics of the load forces, planning movement under microgravity conditions might involve a greater reliance on visual, tactile and/or memory cues to an object's mass. In addition, there might be over-gripping to reduce the consequence of an erroneous estimate of mass. Alternatively, the hand might initially be moved more slowly than normal to allow more time for feedback-based adjustments to grip force. In this regard, a series of experiments has been designed in order to study the effects of a change in gravity on the dynamics of prehension, on the kinematics of upper limb movements and on eye-hand coordination. This report describes the results of some experiments already performed and the scientific objectives of the experiments that will be carried out in the coming years.

1. Background

A stable grip on hand-held objects is of primary importance to secure lifting and moving actions, particularly when the objects are used as tools. Stabilisation depends on applying a strong enough grip force normal to each finger-object contact surface such that sufficient friction is generated to resist the load force acting tangentially to the contact surfaces. Studies of the forces employed in the dexterous handling of objects using a precision grip have found that the grip forces are optimised to prevent accidental slips, and yet are not so excessive as to crush a fragile object or to cause muscle fatigue (Johansson & Westling, 1984; Westling & Johansson, 1984). Grip force must be greater than weight and the inertial load of the object to be moved. In order to ensure secure object manipulation without slip, the grip-load force ratio has to be maintained slightly above the minimum required to prevent slip, according to the friction between skin and object (Johansson & Westling, 1984).

Contribution of the ESA Topical Team in Life Sciences

Eye-Hand Coordination

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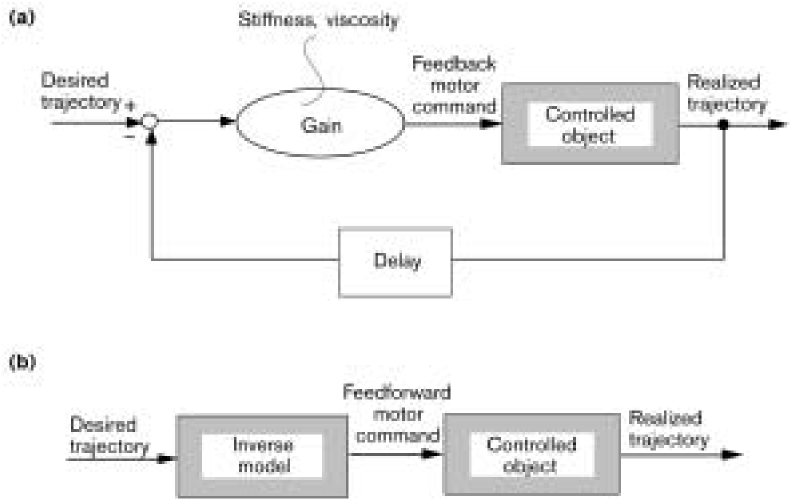


Fig. 1. Feedback and feedforward control of a controlled object. a: the feedback control compares the realised and the desired trajectories in order to compute an error, which serves to generate the feedback motor command after a certain delay. b: the feedforward control uses an inverse dynamics model to calculate the motor command necessary to realise the desired movement. (Adapted from Kawato, 1999.)

Flanagan & Wing (1993) examined grip force modulation as subjects performed either point-to-point or cyclic arm movements with a hand-held 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. The grip forces were modulated in parallel with the load forces, regardless of the object's surface friction or the frequency of movement applied to the object. That is, the grip forces reflected an anticipation adjustment to the fluctuations in inertial forces.

A recurring question addressed in studies of neuromuscular control is that of the relative contributions of feedforward and feedback control to the generation of a motor command (Fig. 1).

An important concept in neuroscience is that feedforward control stems from the ability to predict future states of the system based on information from past sensorimotor experiences, current sensory information and the intended action. This ability to predict the consequences of a motor command implies that the central nervous system makes use of what is called a 'forward internal model' (Wolpert, 1997). The modulation of grip force in anticipation of load force implies that the nervous system has access to information concerning both the object mass and the kinematics of the forthcoming movement, since changes in either of these require a different grip force. This suggests that the internal models used to predict load forces and generate appropriate grip forces are pretty good. It remains to be proved, however, whether the entire control process of grip-force compensation is based on feedforward, model-based control, or if some components of the required grip responses are generated through reflex actions.

In this respect, microgravity presents a significant challenge to dexterous object manipulation for a number of reasons. First, the object has no weight. Therefore, a large part of the load forces tangential to the skin are removed. In a modified gravitational environment, the anticipatory grip force used to support the object would need to be modified. However, whereas the removal of the weight of the object has an obvious effect on the total load force that might easily be predicted, the anticipation of inertial forces might also be affected in less obvious ways. Since there is no perception of weight, the important cues by which the mass of the object might be inferred prior to movement

Fig. 2. Frontal view of the experimental set-up. The subject moved the manipulandum up and down between the two elastic bands 20 cm apart. The grip force was measured by strain gauges, the load force was calculated from the vertical object acceleration measured by an accelerometer.

would be missing. Furthermore, in the absence of weight, the momentum of the object will generate tangential forces in unfamiliar directions (except for highly-accelerated movements of the object, the weight of the object dominates such that the net force acting on the object usually has a downward component in normal gravity). All these potential deviations from the expected characteristics of the load forces mean that planning movement under microgravity conditions might therefore involve a greater reliance on visual, tactile and/or memory cues to an object's mass. In addition, there might be over-gripping to reduce the consequence of an erroneous estimate of mass. Alternatively, the hand might initially be moved more slowly than normal to allow more time for feedback-based adjustments to grip force.

In this regard, this Topical Team has designed a series of experiments to study the effects of a change in gravity on the dynamics of prehension, on the kinematics of upper limb movements and on eye-hand coordination. The first experiments were performed between 1999 and 2001 during the 26th , 27th and 31st ESA parabolic flight campaigns. The results of these experiments have been partly published (Augurelle et al., 2003; Witney et al., in press; White et al., submitted). In order to complete these experiments, the Team successfully responded to ESA's 2001 Life Sciences Research Announcement (ESA-RA-LS-01-FLIGHT/PF-009). Three new experiments are recommended for ESA's parabolic flight campaigns over the next 3 years.

Described below are the results of the two experiments already performed and the scientific objectives of the three planned experiments.

2. Performed Experiments

2.1 The Effect of a Change in Gravity on the Dynamics of Prehension

Experiment team: A.S. Augurelle, M. Penta, O. White, J.L. Thonnard

Scientific Objectives

The grip force exerted on a hand-held object during cyclic vertical arm movements was examined at 1 *g* and at different gravity fields (0 *g* and 1.8 *g*) attained during parabolic flights of an aircraft (Augurelle et al., 2003). A modification of the object's weight was obtained without modification of its mass, and thus its inertia was constant across the different gravitational conditions. By contrast, on the ground, the weight of an object cannot be changed without changing its inertial properties. Therefore, the parabolic flight environment offered the unique possibility to study the effect of a change in gravity on the grip force (GF)-load force (LF) coupling while maintaining the inertial component of the load unchanged. The subjects performed cyclic vertical arm movements while holding an instrumented load during ten parabolic flight manoeuvres. Half of the subjects had never experienced parabolic flights. It was hypothesised that the GF-LF coupling would be progressively adapted to a new gravity level in the naive subjects, while it would be appropriately adjusted in the experienced subjects from

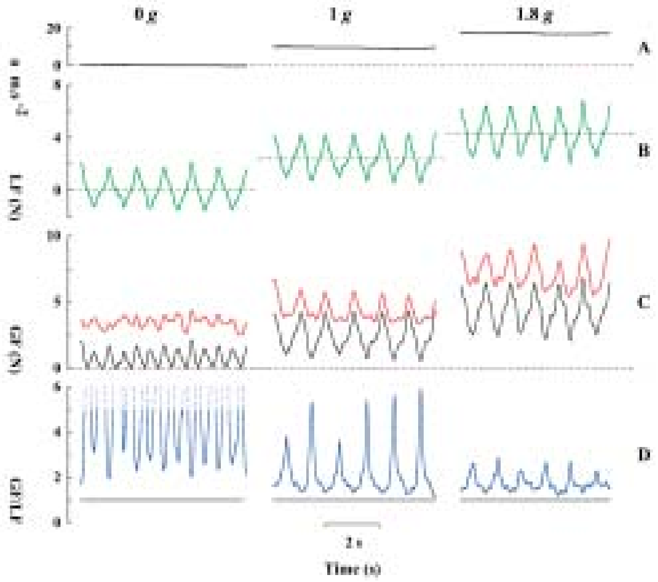


Fig. 3. Records of six contiguous cycles obtained during the stable period in each gravitational phase of the last trial of an NES. The traces presented are the gravity level (A), the load force (B), the grip force (C, red line), the slip force (C, black line), the GF/LF ratio (D, blue line) and the slip ratio (D, black line). The difference between the GF/LF ratio and the slip ratio reflects the safety margin. The friction coefficient was 0.5.

the first time they executed the task in the aircraft.

Description of the Experiment

These experiments were performed during the 26th and 27th ESA parabolic flight campaigns. The grip-load force coupling was measured during cyclic vertical arm movements with an instrumented hand-held object (Fig. 2). It was equipped with strain gauge transducers to measure the GF applied perpendicularly by the fingertips on two parallel brass discs, 30 mm in diameter and 30 mm apart, which served as the grasping surfaces. An accelerometer mounted on the top of the object recorded the acceleration along its vertical axis. The vertical LF resulting from the gravitational and the acceleration-dependent inertial force was calculated as the product of the mass and the vertical acceleration of the object as measured by the accelerometer.

The subject was seated in a chair with an attached seat belt. At a signal from the experimenter, the instrumented object was grasped between the thumb and index finger of the right hand. Cyclic vertical arm movements were made at a frequency of approximately 1 Hz, aided by a metronome. The amplitude of the oscillations was maintained by limiting the range of movement to lie within two parallel rubber bands spaced about 20 cm apart (Fig. 2), which served to guide the endpoints of the arm displacement.

The experiments were performed at 0 *g*, 1 *g* and 1.8 *g* during the parabolic flights. Each subject grasped the instrumented object and started the cyclic movement during the 1 *g* phase, about 30 s before the start of the pull-up phase. The movement was performed throughout the whole parabola and 30 s after the restoration of the 1 *g* condition. Thus the grip force and object acceleration were recorded continuously for 120 s, while the simulated gravity went successively from 1 *g*, to 1.8 *g*, 0 *g*, 1.8 *g*, and back to 1 *g*. Two subjects were examined per flight. On each flight, the non-experienced subject (NES: no previous 0 *g* experience) performed the experiment on the first 15 parabolas, and the experienced subject (ES) was tested during the last 15. In this way, the NES experienced microgravity for the first time as the task was performed during the first parabola. During the 15 first parabolas, the ES was not specifically involved in a manipulation task.

Results

The GF-LF coupling in the different gravitational environments attained during parabolic flights is shown in Fig. 3. These signals were obtained during the last trial of an inexperienced subject. In this typical

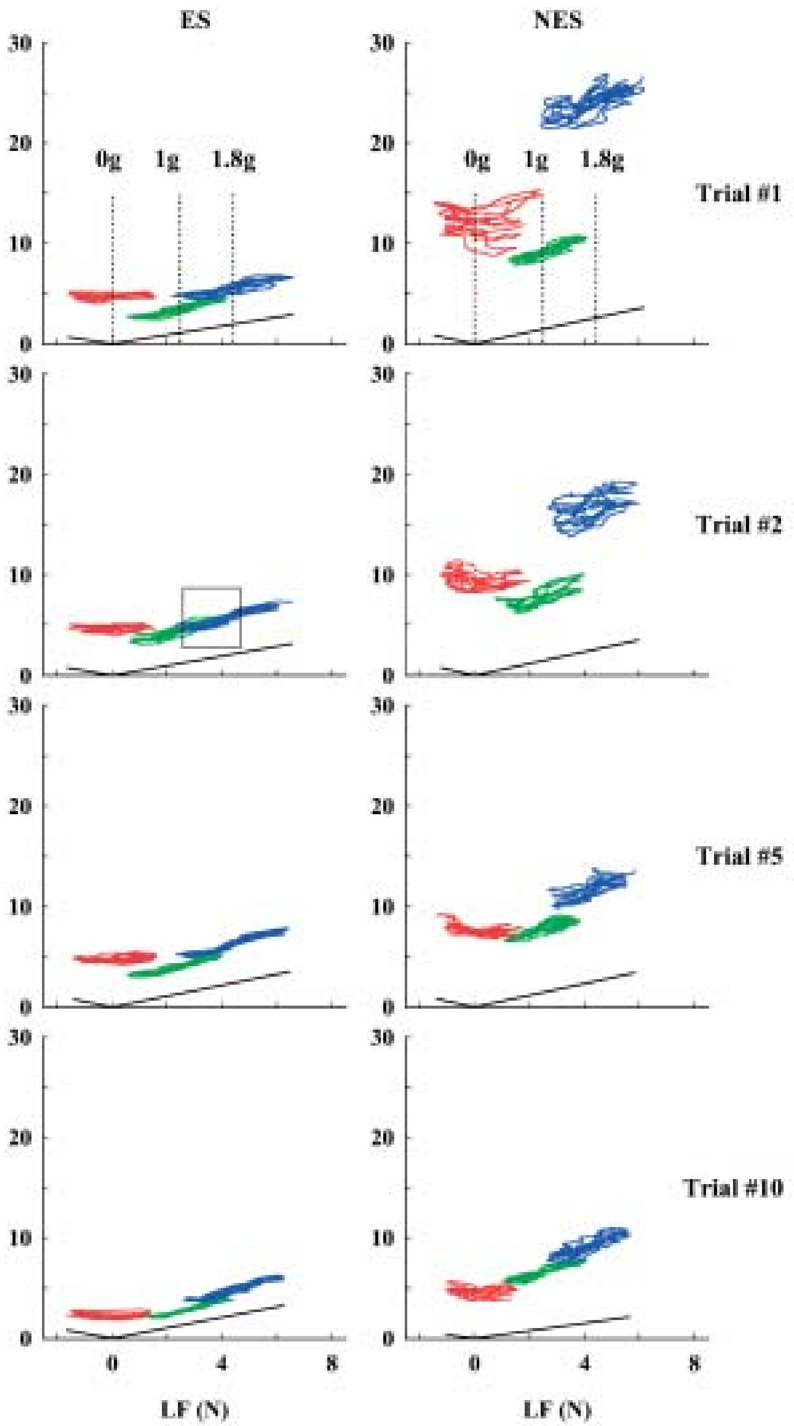


Fig. 4. The grip force-load force relationship measured during six arm-cycles under three gravity levels during the first, second, fifth and tenth trials in an experienced subject (ES) (left column) and a non-experienced subject (NES) (right column). The dotted lines in the upper panels represent the object weight in each gravitational level. The slip force is presented by a straight line according to the friction coefficient of each trace. The inset in the left column shows the overlap between the load force ranges observed at 1 g and 1.8 g. Trial #1 of the NES and the ES corresponded to the first and the 15th parabolas of the aircraft, respectively.

parabola, the aircraft's vertical acceleration was 9.55 ± 0.26 $m\ s^{-2}$ at 1 *g*; 17.07 ± 0.24 $m\ s^{-2}$ at 1.8 *g* and 0.11 ± 0.17 m s-2 at 0 *g* (Fig. 2A). The load force oscillated around the object weight (dotted line) of 2.5, 4.5 and 0 N at 1, 1.8 and 0 *g*, respectively (Fig. 3B).

In normal 1 *g* conditions, the load force reached a maximum at the bottom of the trajectory where the gravitational and the object accelerations were acting in the same direction. The minimum load force occurred at the top of the trajectory, where the object acceleration was opposed to that of gravity. At 1 *g* and 1.8 *g*, the load force was always positive because the downward acceleration of the object required by the frequency and amplitude of the movement was always less than the acceleration due to gravity. In microgravity, the object had to be accelerated both upwards and downwards because gravity no longer accelerated the object downwards, and thus the load force was positive and negative in the lower part and in the upper part of the trajectory, respectively. The amplitude of the load force fluctuations was fairly similar across gravitational environments (about 3 N), suggesting that the NES in this trial was able to maintain the constraints of the imposed movement (1 Hz and 20 cm). In each gravitational phase, the grip force (red line; Fig. 3C) increased and decreased when the load force rose and fell, respectively. At 0 *g*, the grip force increased again at the top of the trajectory to prevent the object from slipping between the fingers when the object was accelerated downwards. The grip force was always greater than the slip force (black line, Fig 3C), indicating that no slippage occurred. Moreover, it was interesting to note that the mean level of the

Table 1. The Four Levels of Equivalent Tangential Loads.

Load Conditions	Levels	Gravity (g)	Mass (g)	Distance (cm)	Additional load	GL (N)	IL (N)	Tangential Load (N)
1	1	2g	400	20	–	2m2g	2ma	2m(2g+a)
2	2	2g	200	40	–	m2g	m2a	2m(g+a)
3		2g	200	40	+	m2g	m2a	
4		1g	400	20	–	2mg	2ma	
5	3	1g	200	40	–	mg	m2a	m(g+2a)
6		1g	200	40	+	mg	m2a	
7	4	0g	400	20	–	0	2ma	2ma
8		0g	200	40	–	0	m2a	
9		0g	200	40	+	0	m2a	

Gravity: gravitation in *g* (*g* = 9.81 ms^{-2}); Mass: mass of the object; Distance: object displacement; Additional load: presence (+) or absence (-) of the 200 g mass on the arm; a: object acceleration; GL: gravitational load; IL: inertial load; Tangential Load: GL + IL

grip force modulation was large enough to prevent slip for any load, suggesting that the modulation was not necessary. Peaks of load force were always precisely synchronised with a similar peak in the grip force so that the GF/LF ratio was minimum and highly reproducible at these times (Fig. 3D). In contrast, when the load force was minimum, the GF/LF ratio was more variable and reached its maximum because the grip was not completely released or was even re-increased.

The adaptation of the GF-LF relationships in each gravitational condition is shown in Fig. 4 across four representative trials. The left column displays typical traces recorded from an experienced subject (ES), and the right from an inexperienced subject (NES).

Both subjects modulated their grip force in phase with the load force fluctuations induced by the object acceleration in each gravitational condition, starting from their first trial. The ES used the same GF-LF relationship from the first to their last trial in the aircraft. A near-continuous grip-load force relationship was established across the different gravitational conditions (Fig. 4, ES). Note that the level of the GF modulation at 0 *g* remained slightly above that observed at 1 *g*. Conversely, when faced with a new gravitational field for the first time, the NES used a dramatically increased grip force at 0 *g* and 1.8 g (Fig. 4, NES). By decreasing both the level and the variance of grip force throughout the ten trials, the NES progressively tends towards a single GF-LF relationship across the gravitational environments. This process started at the second trial and was achieved after the fifth.

Figure 4 also shows that same load force ranges were obtained by varying separately the acceleration of gravity and the acceleration of the object. We observed an overlap in the load force with low gravitational acceleration (i.e. 1 *g*) and high object acceleration (i.e. bottom of the arm trajectory), and in a high gravitational acceleration (i.e. 1.8 *g*) with a low object acceleration (i.e. top of the arm trajectory). Even though the upper limb was in different simulated gravitational fields, the same coupling between the grip force and load force was observed after the information was integrated, i.e. from the first trial for the ES and after the fifth trial for the NES.

2.2 Do Gravitational Environments Alter the Grip-Load Force Coupling at the Fingertips?

Experiment team: O. White, J. McIntyre, A.S. Augurelle, J.L. Thonnard

Scientific Objectives

The relationship between the normal grip force (F_n) and the tangential force (F_t) was examined while moving an object up and down in different gravitational environments (White et al., submitted). Through a variety of test conditions, the inertial and gravitational components of the forces acting on the limb were varied independently. The inertial components were modified by varying the mass of the load or the mass of the limb (ballast weight on the forearm). The weight of the limb and load were varied by varying the effective gravitational field. In this way, it was possible to generate equivalent magnitudes of loads at the fingertips while the mechanical constraints on the upper limb and thus the motor commands required to move the arm were modified. Similarly, certain trials required similar motor commands to move the arm, but different grip forces to maintain the object safely in the grasp.

Description of the Experiment

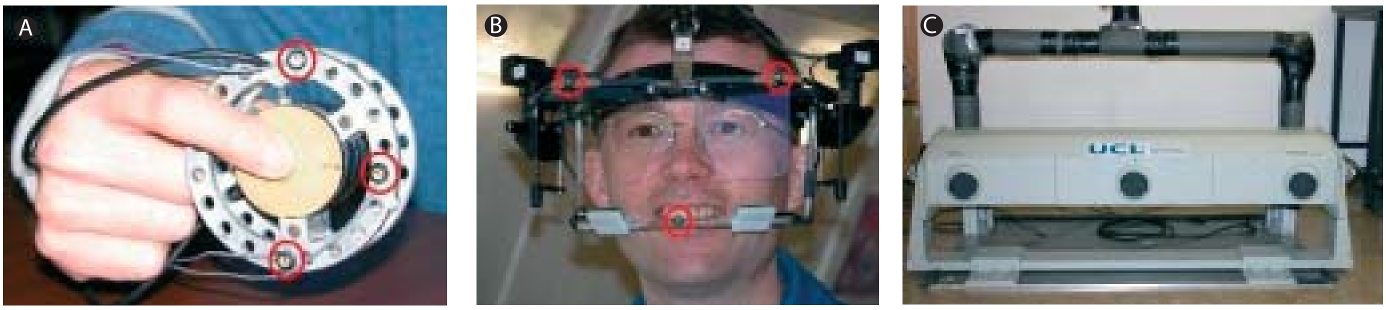
This experiment was performed during the 31st ESA parabolic flight campaign in 2001. Five right-handed subjects (aged 30-48 years), highly experienced in parabolic flights, participated in this study. They had to move an instrumented object up and down continuously in the different gravity fields (1 *g*, 1.8 *g* and 0 *g*) induced by parabolic flights. The imposed movement frequency was 1 Hz; the object mass was either 200 g or 400 g; the amplitude of movement was constrained to 20 cm or 40 cm, and an additional mass of 200 g could be secured around the forearm. The coordination between the grip force normal to the surface and the tangential load was examined under nine loading conditions (see Table 1).

Each subject performed the task over 15 complete parabolas in the aircraft. In the five first trials (P1-P5), the task was performed with a 400 g mass displaced by 20 cm at a frequency of 1 Hz ('400g20cm'). In the second series of five trials (P6-P10), the mass was reduced by half and the amplitude of movement was doubled ('200g40cm'). As the frequency of movement was kept the same (1 Hz), the acceleration was also twice as great, resulting in an equivalent inertial load but an decreased gravitational load. In the last five trials (P11-P15), the 40 cm movement was performed with the 200 g mass but a ballast brace of 200 g was placed around the wrist of the subject ('additional mass'). In this case, the inertial and gravitational components of the load were the same as in the 200g40cm case, but the inertial and gravitational components of the arm were increased. Table 1 shows that, among the nine load conditions, four levels of equivalent tangential force acting on the fingertips could be reproduced while the load imposed on the upper limb was different owing to different gravity levels.

Results

The main finding was that the magnitude of the normal force was adequately adjusted for each maximum of load so as to maintain the same minimal ratio between the normal force and the destabilising tangential load (F_n/F_t) in the nine loading conditions. The subjects were able to maintain this optimal ratio in different contexts of mass, gravity and upper-limb acceleration. For equivalent loads at the fingertips at 1 *g* or 2 *g*, the subjects used the same grip force despite the fact that it required more force to displace the arm in hypergravity. Furthermore, the normal force was modulated with and thus anticipated the effects of tangential force, in

Fig. 5. The experimental platform includes (A) two force-torque transducers measuring the full six components of force and torque (F_x, F_y, F_z; T_x, T_y, T_z), (B) a Chronos video-based 3-D binocular eye movement recording system, (C) a 3-D movement tracking system measuring the kinematics of the instrumented object grasped between the fingers and the Chronos helmet (note the LEDs inside the red circles) .



agreement with previous works (Goodwin et al., 1998; Flanagan et al., 1999). These results show that grip force is not related to the muscle commands to the upper limb in a simplistic manner. Grip force is adjusted specifically to the tangential forces that are applied to the fingertips, rather than being tuned to the overall load applied to the limb.

These results further extend the general framework in which the grip-load force coordination is observed. Not only does the grip-load force coupling reflect a general control strategy for any particular grip or mode of transport (Flanagan & Tresilian, 1994) but it was shown that this strategy is used in different environmental (i.e. gravitational) contexts. The similar force ratio observed in the nine loading conditions indicates that dynamic constraints such as gravitational force and inertial resistance of the arm and object are well taken into account in the control of precision grip. The precise temporal coupling between the normal force and the tangential load also shows that the load was correctly predicted and that the normal force was calculated in a feedforward manner based on this prediction. This suggests that the forward model predicting the load can be adjusted to account for various physical contexts. In other words, subjects are able to identify the environmental context and select the appropriate motor program.

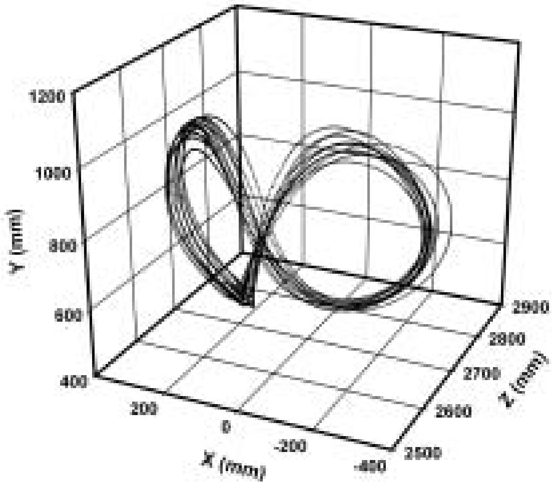
3. Planned Experiments: The Effect of a Change in Gravity on the Eye-Hand Coordination

The Team's proposal in response to ESA's 2001 Life Sciences Research Announcement was recommended by the evaluation committee for flight within ESA's parabolic campaigns. Three experiments are planned to study the effects of a change in gravity on eye-hand coordination. The first and second experiments examine the role of visual and tactile feedback, respectively, in sensorimotor adaptation to microgravity. The third experiment analyses the grip force control in repetitive collisions during parabolic flight to determine whether gravity is taken into account in the prediction of collision load forces.

The equipment for the three experiments includes a platform capable of simultaneously measuring the dynamics of precision grip, the kinematics of the upper limb and 3-D eye movement (Fig. 5).

The dynamics of precision grip will be

Fig. 6. Frontal view of the experimental set-up. The subject is secured by a seat belt on a chair, with the instrumented object grasped, in the frontal plane, between the thumb and the index finger of the right hand. On a signal 20 s before the 1.8 g pull-up phase, the subject is requested to move the object continuously in a figure of '∞'.



measured by two force-torque transducers (ATI Mini 40 force/torque sensors, Industrial Automation, North Carolina, USA) placed under each finger. They measure the full six components of force and torque (F_x, F_y, F_z; T_x, T_y, T_z). The force-torque applied by the fingers will be measured according to the fluctuations of the tangential load force resulting from the gravitational and object accelerations (Fig. 5A).

The kinematics variables will be recorded by a 3-D movement tracking system (OptoTrak 3020, Northern Digital, Ontario, CDN). Studied will be the displacement, angular speed and acceleration of the instrumented object grasped and of the upper limb (Fig. 5C).

In order to investigate eye-hand coordination and the influence of visual feedback on the dynamics of prehension, a 3-D eye-movement recording system is required. The most suitable system is a Chronos video-based 3-D binocular eye movement recording system (Skalar Medical, Delft, NL; Fig. 5B).

The results of these investigations will increase our understanding of the implication of visual/cutaneous feedback and of predictive mechanisms in the planning and execution of arm movements involving hand-held objects.

The three experiments are described below.

3.1 Role of Visual Feedback in Grip-Load Force Coordination during Circular Arm Movements with a Hand-Held Load in Different Gravitational Fields

Experiment team: O. White, P. Lefèvre, G. Blohm, J.L. Thonnard

Scientific Objectives

Eye-hand coordination will be studied by varying the arm trajectory of subjects manipulating an object in novel gravity fields. The coupling between the grip force and the load force will be studied when the vectorial direction of the object acceleration is continuously changed in relation to the gravity during a figure of '∞' arm movement. When one moves an object in the frontal plane following a figure of '∞' trajectory at a constant speed, the object is subjected to the vertical gravitational acceleration and to the centripetal acceleration. The load force

Fig. 7. The effect is investigated of wearing little caps covering the thumb and index finger on the grip force-load force coupling on the continuous manipulation of objects in space.

tends to make the object slip out of the fingers. In order to restrain the object, the normal grip force has to be adjusted to the load force fluctuations. The parameters of movement dynamics (forces and torques) will indicate how the subject is able to anticipate the load force, which depends both on the gravity and the acceleration of the upper limb.

The kinematics parameters (displacement, speed and acceleration) will indicate whether the subject is able to perform the '∞' movements in altered gravitational environments. The intended trajectory could be programmed inappropriately on the basis of an erroneous internal representation of gravity producing changes in the actual movement. The question arises as to how the grip force applied to the object will be adjusted according to the tangential load force perturbations due to the gravitational changes and to errors in the trajectory profile. This issue is of particular interest because horizontal load forces remain unchanged by gravity modifications, whereas this is not the case for the vertical components.

Eye movements and the role played by visual feedback when performing this task in new gravity fields are also of interest. Therefore the gaze behaviour will be studied in order to detect if subjects direct their gaze to critical landmarks and how these landmarks impinge on the action (Johansson et al., 2001).

Description of the Experiment

The subject is secured by a seat belt on a chair, with the instrumented object grasped, in the frontal plane, between the thumb and the index finger of the right hand. On a signal delivered 20 s before the 1.8 *g* pull-up phase, the subject is requested to move the object continuously in a '∞' figure trajectory, bypassing two horizontal visual targets, one in each loop of the '∞' shape (Fig. 6).

The subject is instructed to maintain the movement constant across each gravity phase of the parabola. Moreover, the subject will perform half of the trials with saccades between the targets and half with his gaze fixed on the midpoint between the targets. Two subjects will be studied on each flight, each for 15 parabolas.

3.2 Role of Cutaneous Feedback in the Grip-Load Force Coordination during Circular Arm Movement with a Hand-Held Load in Different Gravitational Fields

Experiment team: A. Smith, J.S. Langlais, O. White, J.L. Thonnard

Scientific Objectives

It has already been established that after relatively brief exposures (about five episodes of 30 s each) to microgravity, subjects learn to adapt their grip forces to compensate for the altered tangential forces on the skin (Augurelle et al., 2003). Since previous studies (Smith et al., 2002; Saels et al., 1999) had clearly shown that this adaptation to unexpected load forces is mediated by cutaneous afferents on the skin of the fingers and palm at 1 *g*, there is every reason to believe that the adaptation to microgravity involves the same tactile receptors. This study will try to define the minimal tactile spatial acuity needed to adapt the grip forces normally used in a 1 *g* environment to microgravity. The effect of wearing little caps covering the thumb and index finger (Fig. 7) on the grip force-load force coupling on the continuous manipulation of objects will be investigated during parabolic flights. The caps are made of materials that are evaluated before parabolic flight for their capacity to filter variations in tangential force.

Description of the Experiment
The subject is secured by a belt on a chair, with the instrumented object grasped, in the frontal plane, between the thumb and the index finger of the right hand. On a signal delivered 20 s before the 1.8 *g* pull-up phase, the subject is requested to move the object continuously in a figure of '∞' trajectory in the frontal plan. He is instructed to maintain the movement constant across each gravity phase of the parabola. The subject is trained at 1 *g* before the flight campaign. Two subjects will be studied on each flight, each for 15 parabolas.

3.3 Grip Force in Controlled Collisions in Different Gravitational Fields

Experiment team: A. Wing, J. McIntyre, A. Witney, R.M. Bracewell, O. White, J.L. Thonnard

Scientific Objectives
Studies (see Wing, 1996, for review) have shown that grip force used to overcome load forces and torques in lifting and inertial forces and torques in moving is adjusted in anticipation of the load (Johansson, 1996; Wing, 1996; Jenmalm et al., 1998; Wing & Lederman, 1998). Prediction may not be correct and in many cases predictive feedforward control may be supplemented by feedback control (Witney et al., 2001). A problem is then to dissociate the two forms of control in the behavioural record. One method is to limit analysis to the initial phase of an action, say the first 20 ms, which is too short a period for feedback correction to be implemented. An alternative is to study collisions in which the time period over which the load is applied is too short to allow a feedback loop to operate (Johansson & Westling, 1988; Turrell et al., 1999). The proposal is to analyse grip force control in repetitive collisions during parabolic flight to determine the role played by gravity in prediction of collision load forces. The task will blend elements of two paradigms used extensively by Wing in his previous research: cyclic movement and collision.

Description of the Experiment
The subject is secured by a seat belt on a chair with the instrumented manipulandum grasped between the thumb and the index finger of the right hand. He performs a targeted tapping task with the manipulandum while eye movements and kinematics of the upper limb are monitored. He briefly taps the manipulandum randomly on surfaces placed above and below the hand's neutral position.

Analyses will include modulation of grip force with collision load force and the timing of eye movement relative to tap events. The analyses are expected to show dependence of timing and amplitude of peak grip force rates on gravitational conditions. A primary focus is on the extent to which there is progressive adaptation over successive cycles after the transition between 2 *g* and 0 *g* and between 0 *g* and 2 *g*.

4. Perspectives

Microgravity provides an excellent environment to assess the properties of the motor system. 'Changes' in gravity can be considered as perturbations to the manipulation task. These perturbations are very challenging to the motor system because they require rapid adaptation to the changing environment. They provide a powerful tool for the analysis of coordination underlying dexterous manipulation, as shown by the studies reviewed above.

In the future, we should be able to investigate the respective roles of feedforward and feedback in more complex motor tasks and assess the adaptation capabilities of the motor system. This could be done by manipulating visual and haptic feedback during motor tasks performed in microgravity. Using methods of robotics and virtual reality combined with measurements of human motor behaviour, we can explore movement-control strategies. These studies could also contribute to the design and control of robotic arms to be used in challenging environments such as space. Several examples of possible experiments are outlined below.

4.1 Interdisciplinary Studies of Robotics and Human Motor Control

The interaction between neuroscience and robotics is two-fold: neuroscience provides knowledge about the nervous system that can be used to build anthropomorphic robots; and anthropomorphic robots are a powerful platform for experimental validation of theories and hypotheses formulated by neuroscientists. One can imagine an experiment investigating eye-hand coordination using neurobiologically-inspired control algorithms in a robot installation that operates in different gravitational fields. A number of learning strategies have been proposed in the field of robotics for the adaptive control of complex manipulators. The ability of these strategies to adapt to novel gravitational environments can easily be tested. Robots implementing these algorithms can be trained to perform optimally in 1 *g*. They can then be placed in altered gravity fields to see how the control adapts to the new constraints. Comparisons can then be made between the actions of the robot in the novel environment and the actions of human subjects faced with the same challenge.

4.2 Studies of Sensorimotor Integration Through Sensory Conflicts and Virtual Reality

Effective control of movement requires the integration of information from a variety of sensory modalities, such as vision, cutaneous touch, muscle proprioception and vestibular. These modalities are complementary; the combination of sensors provides more information than any one modality alone. An interesting way to study how the central nervous system calibrates and integrates all this information from different sources is to introduce sensory conflicts by which one sensory modality is perturbed with respect to the other. Such conflicts can be induced using techniques of virtual reality in which the experimenter can influence the reliability of sensory information provided to the subject. For example, one can create a world in which a 10 cm movement of the hand is displayed as a 20 cm movement in the visual field; this is a proprioceptive-visual conflict. Under terrestrial conditions, muscle proprioception is important in recalibrating for the changed visuo-motor relations. Novel gravitational environments provide a unique experimental manipulation of proprioception for examining the adaptability of such recalibration.

Vestibular information is another class of sensory input which must be integrated with muscle proprioception. It normally contributes to tasks involving whole-body movement. Consider a task in which one hand is used to provide grip for stabilisation when picking up an object with the other hand at a horizontal or vertical distance of more than arm's length. Because of the distance, the subject must move the whole body. The grip used by the stabilising hand may then provide an index of prediction of loading caused by whole-body movement. Manipulating the gravitational field is one of the very few means for modulating the sensory inputs provided by the vestibular system.

In summary, the ability to perform experiments in altered gravity environments provides a unique opportunity to study vestibular-proprioceptive and visual-proprioceptive sensory integration for motor control.

4.3 Interactions between Sensory and Cognitive Influences on Motor Control

Our ability to function in the physical world is not based exclusively on sensory signals. Through experience, we create cognitive representations of how the world works. For instance, a human subject who observes an approaching ball will trigger a interceptive response earlier for a ball that is falling from above than for the same ball that is rising from below, even though both balls follow the same trajectory in terms of distance, velocity and acceleration (Hubbard, 1995; Senot et al., in preparation). This phenomenon can be interpreted as a cognitive prediction of the effects of gravity on the ball – the subject anticipates that the ball will accelerate or decelerate depending on the direction of movement. On Earth, sensation of gravity can easily define the up and down directions that are the source of this effect. In microgravity, however, it appears that additional cues in the environment (such as the direction of lighting, the spatial layout of the module) can nevertheless induce a perception of 'up' and 'down' that leads the subject to anticipate the effects of gravity even though it is no longer present (McIntyre et al., 2001). Experiments performed in altered gravitational environments can shed light on the construction of these cognitive representations and how they affect the control of movement. Furthermore, such studies may aid in the conception of countermeasures or tools that might be provided to astronauts to compensate for the missing stable orientation reference that is usually provided by gravity.

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References

Augurelle, A.S., Penta, M., White, O. & Thonnard, J.L. (2003). The Effect of a Change in Gravity on the Dynamics of Prehension. *Exp. Brain Res.* **148**, 533-540.

Flanagan, J.R. & Tresilian, J.R. (1994). Grip-Load Force Coupling: a General Control Strategy for Transporting Objects. *J. Exp. Psychol. Hum. Percept. Perform.* **20**, 944-957.

Flanagan, J.R. & Wing, A.M. (1993). Modulation of Grip Force with Load Force during Point-to-Point Arm Movements. *Exp. Brain Res.* **95**, 131-143.

Flanagan, J.R., Nakano, E., Imamizu, H., Osu, R., Yoshioka, T. & Kawato, M. (1999). Composition and Decomposition of Internal Models in Motor Learning under Altered Kinematic and Dynamic Environments. *J. Neurosci.* **19**, RC34.

Goodwin, A.W., Jenmalm, P. & Johansson, R.S. (1998). Control of Grip Force when Tilting Objects: Effect of Curvature of Grasped Surfaces and of Applied Tangential Torque. *J. Neurosci.* **18**: 10724-10734.

Hubbard, T.L. (1995). Cognitive Representation of Motion: Evidence for Friction and Gravity Analogues. *J. Exp. Psychol. Learn. Mem. Cogn.* **21**(1), 241-254.

Jenmalm, P., Goodwin, A.W. & Johansson, R.S. (1998). Control of Grasp Stability when Humans Lift Objects with Different Surface Curvatures. *J. Neurophysiol.* **79**, 1643-1652.

Johansson, R.S. (1996). Sensory Control of Dexterous Manipulation in Humans. In *Hand and Brain: The Neurophysiology and Psychology of Hand Movements* (Eds. A.M. Wing, P. Haggard & J.R. Flanagan), Academic, San Diego, USA, pp381-414.

Johansson, R.S. & Westling, G. (1984). Roles of Glabrous Skin Receptors and Sensorimotor Memory in Automatic Control of Precision Grip when Lifting Rougher or More Slippery Objects. *Exp. Brain Res.* **56**, 550-564.

Johansson, R.S. & Westling, G. (1988). Programmed and Triggered Actions to Rapid Load Changes during Precision Grip. *Exp. Brain Res.* **71**, 72-86.

Johansson, R.S., Westling, G., Backstrom, A. & Flanagan, J.R (2001). Eye-Hand Coordination in Object Manipulation. *J. Neurosci.* **21**, 6917-32.

Kawato, M. (1999). Internal Models for Motor Control and Trajectory Planning. *Current Opinion in Neurobiology* **9**, 718-727.

McIntyre, J., Zago, M., Berthoz, A. & Lacquaniti, F. (2001). Does the Brain Model Newton's Laws? *Nat. Neurosci.* **4**(7), 693-694.

Saels, P., Thonnard, J.L., Detrembleur, C. & Smith, A.M. (1999). Impact of the Surface Slipperiness of Grasped Objects on Their Subsequent Acceleration. *Neuropsychologia* **37**, 751-756.

Senot, P., Zago, M., Lacquaniti, F. & McIntyre, J. How Downward and Upward Trajectories Influence the Timing of Motor Responses in Virtual Ball Catching, (manuscript in preparation).

Smith, A.M., Chapman, C.-E., Deslandes, M., Langlais, J.-S. & Thibodeau, M.-P. (2002). The Role of Friction and Tangential Force in the Subjective Scaling of Tactile Roughness. *Exp. Brain Res.* **144**, 211-223.

Turrell, Y.N., Li, F.-X. & Wing, A.M. (1999). Grip Force Dynamics in the Approach to a Collision. *Exp. Brain Res.* **128**, 86-91.

Westling, G. & Johansson, R.S. (1984). Factors Influencing the Force Control during Precision Grip. *Exp.Brain Res.* **53**, 277-284.

White, O., McIntyre, J., Augurelle, A.S. & Thonnard, J.L. Do Novel Gravitational

Environments Alter the Grip-Load Force Coupling at the Fingertips? *Experimental Brain Res.*, submitted.

Wing, A.M. (1996). Anticipatory Control of Grip Force in Rapid Arm Movement. In *Hand and Brain: The Neurophysiology and Psychology of Hand Movements* (Eds. A.M. Wing, P. Haggard & J.R. Flanagan), Academic, San Diego, USA, pp301-324.

Wing, A.M. & Lederman, S. (1998). Anticipating Load Torques Produced by Voluntary Movements. *J. Exp. Psychol. Hum. Percept. Perform.* **24**, 1571-1581.

Witney, A.G., Wing, A., Thonnard, J.-L. & Smith A.M. (2001). Feedforward and Feedback Contributions to Precision Grip. In *From Basic Motor Control to Functional Recovery II* (Ed. Gantchev, N.), Sofia, Bulgaria, Prof. M. Drinov Academic Publishing House, pp163-176.

Witney, A.G., Wing, A., Thonnard, J.L. & Smith, A.M. The Cutaneous Contribution to Adaptive Precision Grip. *Trends Neurosci.*, in press.

Wolpert, D.M. (1997). Computational Approaches to Motor Control. *Trends Cog. Sci.* **1**, 209-216.

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