# Haptics-1: Preliminary Results from the First Stiffness JND Identification Experiment in Space

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**Abstract.** On July 28th 2014, 23:47 UTC, the European Space Agency launched the Haptics-1 Kit to the International Space Station (ISS) on its last Automated Transfer Vehicle ATV-5. The Kit reached the station two weeks later, marking the first haptic master device to enter the ISS. The first force-feedback and human perceptual motor performance tests started to take place on December 30th 2014, and are the first of their kind in the history of spaceflight. Three astronauts participated in the Haptics-1 experiment until November 2015, allowing the investigation of the effects of microgravity on various psycho-motor performance metrics related with the usage of haptic feedback. Experiments are conducted following full adaptation to the space environment (after 3 months in space). This paper introduces the Haptics-1 experiment and associated hardware. Detailed experimental results are reported from a first stiffness just noticeable difference (JND) experimental study in space, carried out on the ISS and pre-flight on ground with 3 astronauts. The first findings from the experiment show no major alterations in-flight, when compared to on-ground data, if the manipulandum is secured in flight against a sufficiently stiff reference structure.

**Keywords:** Micro gravity · Just noticeable difference (JND) · Stiffness discrimination · Space · Haptics

## 1 Introduction

To enable further human exploration to neighbouring celestial bodies, telerobotic technologies will have to be used extensively. In a scenario that is gaining increasing popularity among the space community, operators will stay in orbiting stations (e.g. around Mars) and control robotic systems on the surface via


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haptic teleoperation [1,5]. This way, they can remotely prepare human outposts for later human arrival, or conduct ‘remote-in-situ’ geophysical and geoscience research. In order to design haptic teleoperation devices for space, knowledge about potential changes to human motor performance in microgravity is important. The perception thresholds for torque and stiffness, as well as the capability to perform hand-eye coordinated position and torque tracking under long exposure to microgravity, need to be better understood.

Previous studies suggest that microgravity deteriorates human perceptual-motor performance. In [2] the authors showed a deterioration of human arm movement control and stipulate that a decrease in muscle spindle sensitivity in zero-G could be the cause. In general, changes can be related to alterations of cutaneous pressure or with different loading of the joints, muscles and associated sensors. However, often it is unclear whether observed changes are caused by the microgravity itself or by other contributing stressors related with spaceflight [3]. This is especially true for tests performed during short exposure to microgravity, such as during parabolic flight. While existing perceptive motor-performance tests on hand-eye coordination and reaching tasks have been performed in parabolic flights and some during SpaceLab missions with the Space Shuttle, studies involving adapted humans (i.e. at least exposed to microgravity for more than 20 days) to the environment are scarce and limited to the analysis of mental condition and rudimentary hand-eye coordination tasks [4]. Despite the extensive body of literature available on kinaesthetic performance in terrestrial environments, hardly any work is available to date that quantifies such performances under microgravity. The effects of microgravity on torque and stiffness discrimination capabilities in spaceflight are unknown.

It is the goal of this paper to introduce the Haptics-1 experiment of the European Space Agency, which is being conducted on ground (pre-flight) and in-flight on the ISS with multiple ESA, NASA and JAXA astronauts. This paper introduces the Haptics-1 study goals, its hardware Kit consisting of a high resolution force reflective manipulandum (joystick) and its experiment environment for automated in-flight data acquisition. Moreover, it is the goal of the paper to report first results from a stiffness just noticeable difference (JND) identification experiment conducted with 3 astronauts on ground and on-board ISS after full adaptation ($> 3$ months) to microgravity.

## 2 Haptics-1 Study Objectives

The Haptics-1 experiment consists of seven individual protocols to measure (a) the mechatronic performance stability of a haptic impedance controlled joystick in space (system self-test), (b) the variations of human impedance during relax, comply and resist tasks, (d) the hand-eye tracking performance and bandwidth for position and force (e) tracking tasks, the just noticeable differences for (f) force and (g) stiffness discrimination with the upper extremity up to the hand and, (h) the detection thresholds for a combined stiffness and damping contact tasks with virtual environments.

The JND experiments are all conducted with the upper limb in a position closely matching a typical ‘joystick use case’, such as e.g. during aircraft piloting or during robotic operation with a joystick.

All Haptics-1 protocols are performed pre-flight, in-flight on the ISS and if applicable also post-flight, after adaptation to the respective environments. The protocols are performed in ‘wall-mount’ condition and in ‘body-mount’ condition. In Fig. 1, the haptic device (1DOF joystick) is depicted in ‘wall-mount’ configuration on a seat-track interface strip as available also on ISS Columbus module experiment racks. During body-grounded condition, the joystick is worn on a body-vest directly attached to crew (depicted in the inset Fig. 1). The body-mount condition has been added to check whether creating a closed-loop force-path between joystick and the operator hand in space bears perceptive or work-load related advantages. In this case, theoretically, external forces from the joystick should not need to be counteracted by either gravity on ground, or by additional postural control via foot restraints in space. Therefore, this mounting style could be ‘easier’ to use in space. Haptics-1 is currently not intended as a longitudinal study, mainly due to a limitation of available crew time on-board.

All protocols are trained on ground and conducted in space by the astronauts under the help of an automatically guided experiment App on a touch-screen tablet PC (Fig. 1). The Principal Investigator (PI) monitors the conduct from ground via real-time video stream and is enabled to speak on the space-to-ground voice loop with crew if needed.

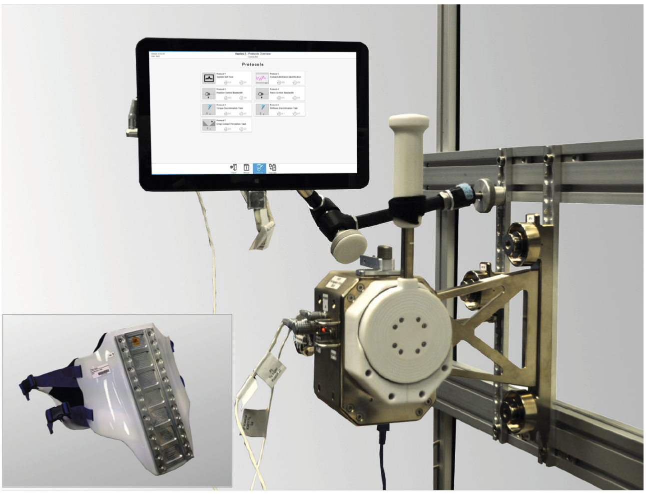


**Fig. 1.** The Haptics-1 flight model before launch (1DOF haptic joystick and touch-screen tablet PC) installed in wall-mount configuration on two seat track strips in a clean-room. The inset shows the body-vest with the same seat track interface that is used to mount the joystick in a body-grounded manner to crew.

## 3 The Apparatus: Haptics-1 Kit

The Haptics-1 Kit contains the 1° of freedom joystick, the touch-screen tablet PC with custom experiment software and all required periphery components (LAN Cables, power adapters, launch containers, storage devices, the body-vest, etc.) inside a flame-proof Nomex experiment container.

The joystick receives 28 V from a station portable power supply. The tablet is connected to the joystick's real-time computer via a point to point LAN cable. A reserve LAN interface exists on the joystick, allowing connection to the ISS Joint Station LAN for bilateral control experiments with a ground unit. The Haptics-1 App on the tablet PC is the sole graphical user interface (GUI) for crew. It guides the user through all individual experiment steps and allows the management (save, discard and retrieve) of the experiment data. For re-usability of the Kit, all software is easily exchangeable via file up-load through USB. The Kit is safety certified for human-in-the-loop (medical) data acquisition on-board the ISS and withstands all environmental loads related to ground transport, launch to space and use within the ISS environment.

### 3.1 The 1DOF Joystick

The 1DOF joystick integrates an Intel Atom 1.6 GHz computer running a Linux operating system with a Xenomai real-time patch. This computer runs the Haptics-1 joystick and experiment control software that interacts with the GUI of the Tablet. Via an EtherCAT bus, the real-time computer connects to a brushless DC motor controller that controls an ILM50x14 RoboDrive direct-drive actuator whose torque ripple is compensated to provide a smooth, ripple-free output to the handle-bar. On the motor shaft, an absolute position encoder provides a 21 bit position signal. The motor is connected via a capstan reducer to a custom built, strain-gauge based, joint-output torque sensor located just before the handle-bar. The actively controlled joystick can act as a pure position or torque source, or can render an impedance through its integrated closed-loop joint torque control running at a cyclic 2 kHz rate. Upstream current inhibitors, thermal fuses (for touch temperature monitoring) and joint limit microswitches as well as handle-bar dead-man microswitches ensure safe operation of the joystick under all circumstances when human-in-the-loop experiments are performed. The joystick has a range of motion of ±60° around the centre position depicted in (Fig. 1). The joystick can render a maximum continuous torque of ±12.0 Nm. The real-time computer running on the joystick encrypts all experiment data with 4096-bit encryption to protect the 'medical rated' data. Data is automatically transmitted via Data Distribution Services (DDS) to the tablet PC for retrieval via USB by crew after the experiment.

### 3.2 Joint Control Performance

For the Stiffness JND protocol, the joystick enters joint impedance control mode. The joystick can then render stiffnesses in the range from 0–0.286 kNm/rad and

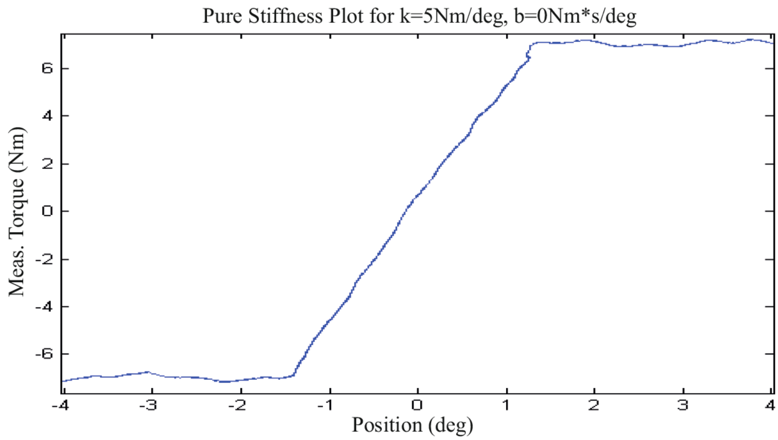



**Fig. 2.** Stiffness response of the Haptics-1 flight-model joystick during an interaction with an operator (simulated spring with constant $k = 5\,\text{Nm/deg}$).

also damping in the range from 0–1.1 Nms/rad. The achievable torque resolution in closed-loop joint torque control is as low as 7 mNm and torque ripple is less than 6.7 mNm, which is hardly perceivable by an operator. A recording of a rendered virtual spring with stiffness $k = 5\,\text{Nm/deg}$ on the flight-model joystick is depicted in Fig. 2, during interaction with a human operator.

Individual step responses of the position and joint torque controllers are depicted in Fig. 3. For the recording of the position step response, the joystick output was free to move (Fig. 3a). For the torque step response recording it was locked down at its output (Fig. 3b). The joint position controller is intended

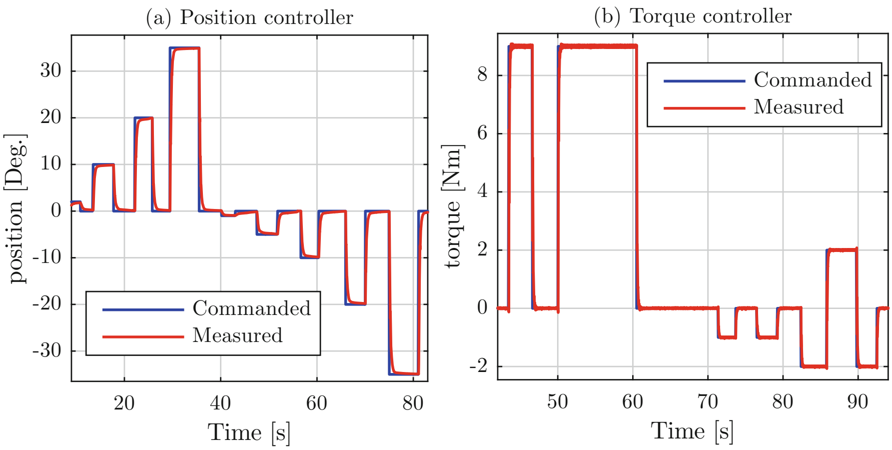



**Fig. 3.** Varying magnitude step responses of the Haptics-1 joysticks joint position controller (a) and joint torque controller (b). During recordings (a) the joystick was free to move, whereas the joystick output was clamped mechanically in (b). (Color figure online)

mainly for aligning the handle-bar to a reference pose during specific sequences in any of the protocols. This is why it is tuned "soft" to exert appropriately low speeds when the bar is handheld. The rise-time to 90 % output takes 550 ms. The joint torque control is tuned very stiff, in order to allow crisp force feedback to be rendered to the operator and also to enable the high bandwidth joint impedance control. The rise-time to 90 % output for the torque control is less than 180 ms.

## 4 Stiffness JND Identification Ground vs. Space

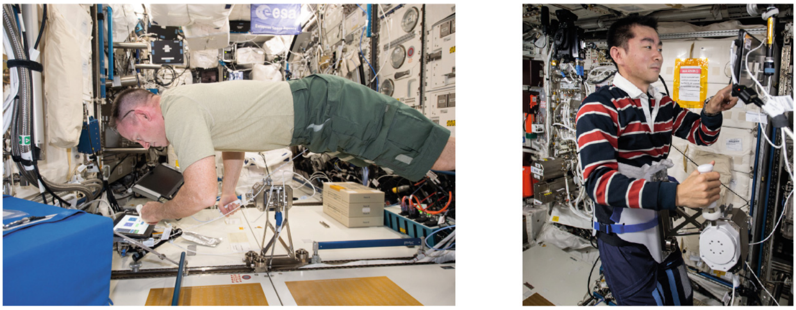
Multiple stiffness just noticeable difference (JND) tests have been performed as part of the Haptics-1 experiment campaign on-board the ISS in the time frame between January 5th and November 27th 2015. Three astronauts participated in baseline data collection (BDC) on ground before flight and in-flight data collection on the ISS. Two of the astronauts were trained U.S. air force test pilots and the third one a medical professional with emergency room experience. All study participants have provided signed informed consent via NASA and integrated ISS medical boards, and the study was evaluated by the ethics commission of Delft University of Technology.

### 4.1 Method

The JND experiment follows a 2-alternative forced choice (2AFC) design with $n = 200$ trials in which a stiffness reference level (e.g. Stimulus A) is compared with one of four modified test levels (e.g. Stimulus B) in multiple binary comparison tests. All trials are randomized with respect to A and B distribution as well as with respect to the reference level locations within the 200 trials. The experiment conduct can be considered double-blinded, since the experiment is hard-coded and automated on the Haptics-1 Tablet PC and 1DOF joystick.

The stiffness reference level is selected to be 1 Nm/deg., and the randomized test levels were at ±40 %, ±25 %, ±15 % and ±5 % of the reference stimulus (50 repetitions each). The 5 % test value is the lowest threshold that can still be rendered accurately by the Haptics-1 1DOF joystick, which is why this 'lowest possible threshold' series was chosen. During each trial, a pair of two stiffness samples is presented to the crew member via the manipulandum's impedance controller. The astronaut can select which one of the two stimuli (A or B) to probe via the GUI. Following the probing of both stimuli (they are free to choose back and forth between them), the candidate is asked to select the stiffer one of the two (A or B) via a dedicated selection button on the GUI. After selection, the next pair is presented to the astronaut until all 200 repetitions are completed. Each crew member conducts two test sessions on two consecutive days, one for the wall-mount and one for the body-mount data acquisition configurations (Fig. 4). For all trials, the astronauts are instructed to keep their arm parallel to a sagittal plane and similar to operating a joystick for robotic controls.

In space, the experiment was only performed after 3 months into the mission of each crew member. This way, potential dominant effects related with other



(a) wall-mount session (b) body-mount session

**Fig. 4.** Astronauts on-board the International Space Station (Butch Wilmore, NASA; Kimiya Yui, JAXA) perform the Stiffness JND protocol of Haptics-1. Joystick in wall-mount setup in (a) and in body-mount (i.e. body-grounded force-feedback) in (b). Experiments done on ISS 3 months in flight.

stressors are minimized. A static design with 200 trials and four levels was chosen in order to present an overview over a large discrimination threshold range (not only a minimum threshold). Moreover, the levels were tailored by ground experiments with non-astronauts. The exact number of 200 trials was also a trade-off between science return and available crew-time on-board ISS. Every participating astronaut received ground training, performed pre-flight BDC and received a de-brief on-board prior to in-flight experiment conduct.

For data post-processing, the crew ratings for each stimuli level are counted and converted into a "percentage correct" for each test level and subject (50 correctly identified 'stronger' stimuli representing 100 % correct). A test subject achieving a percentage of at least 75 % correct estimates in one test level is considered to 'notice the difference' for the scope of this report. The paper reports boxplots for the combined subject data of the 3 astronauts. The test data is additionally checked with 2-way ANOVA and paired t-tests along all dimensions.

## 5 Stiffness JND Results

### 5.1 Ground, Body vs. Wall Mount Measurements

The boxplots of Fig. 5 show that the two attachment conditions do not cause stiffness JND results to differ on ground (confirmed by paired t-tests on all tested levels). The stiffness detection threshold lies between 5–15 % for both conditions, which can be seen also without the fitting of a psychometric function. The measurement range is appropriate in both cases to detect the transitioning from above to below the 75 % detection threshold. The difference detection of the 5 % level is more difficult than the 40 % level detection for the entire group ($p < 0.02$, $F = 10.5$) in wall-mount condition. In body-mount condition, the effect is even stronger ($p < 0.001$, $F = 64.1$). While in body-mount condition

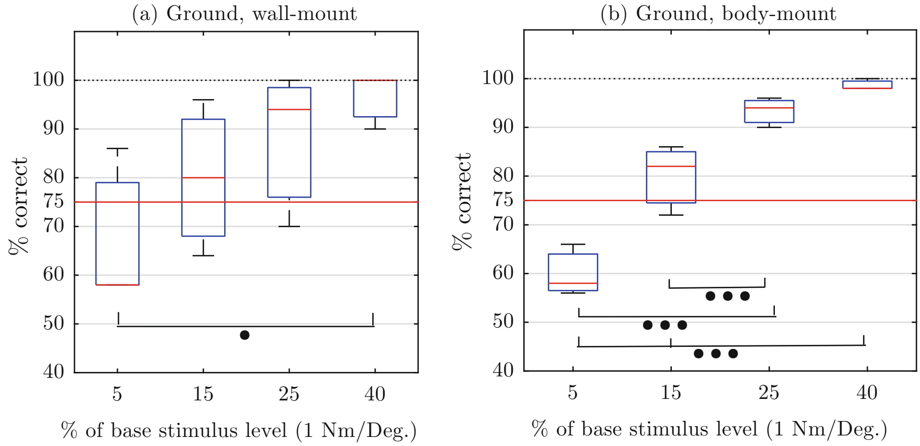



**Fig. 5.** Group stiffness JND results (three astronauts). Comparison of wall-mount (a) vs. body-mount (b) configuration on ground, obtained during pre-flight baseline data collection (• : $p < 0.02$; •• : $p < 0.01$; • • • : $p < 0.002$). (Color figure online)

there are no significant performance differences between subjects, in wall-mount, one subject performed worse than the other two, which causes more spread of the data.

### 5.2 Micro-G, Body vs. Wall Mount Measurements

The data presented in Fig. 6 shows slight variations between wall-mount and body-mount JND thresholds in space. Whereas the detection threshold for the wall-mount configuration lies between 5–15 % of the base stimulus, the body-mount configuration indicates a worsening towards the 15–25 % range for the combined subject results. The difference between the detection rates for the individual stimuli levels are more profound in space, with all levels different to each other in wall-mount configuration ($p < 0.01$, $F = 12.7$) and more strongly so in body-mount configuration ($p < 0.002$, $F = 20.72$). Paired t-test performed between equal difference levels of the two mounting conditions reveals no difference between the mounting conditions.

### 5.3 Ground vs. Micro-Gravity

The only difference detectable between the ground and space data-sets is apparent in the body-mount configuration, in which the 15 % difference level becomes worse in-flight with respect to ground ($p = 0.039$), explaining the apparent worsening of the overall detection threshold for the group in the boxplot in Fig. 6. No overall difference in the combined wall- and body-mount data results can be observed between in-flight and ground measurements.

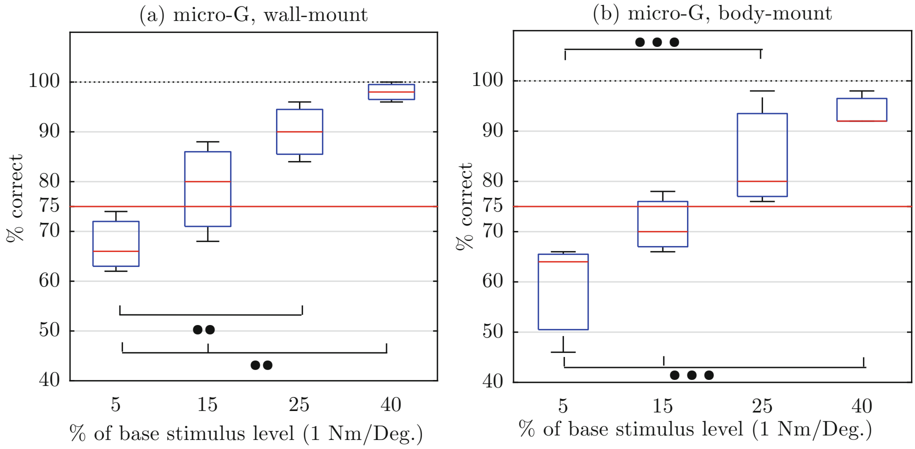



**Fig. 6.** Group stiffness JND results (three astronauts). Comparison of wall-mount (a) vs. body-mount (b) configuration in-flight on board the International Space Station (● : $p < 0.02$; ●● : $p < 0.01$; ● ● ● : $p < 0.002$). (Color figure online)

## 6 Discussion

It appears from the data above, that humans are very good at adjusting to novel environments, with no overall differences visible in Stiffness discrimination between ground and space after their 3 month adaptation to the micro-gravity environment. Moreover, the results above show strikingly little variation between subjects, considering that the background of test candidates was rather different. This suggests that the protocol automatic conduct, the performance of the hardware and the selection of experiment parameters are appropriate for this experiment. Human palpation from orbit could potentially be performed with the same perceptive capability than on ground, which could be good news for using telerobotics from space (if the teleoperation system itself doesn't limit the perception). Certainly, further analysis with additional subjects is ongoing, however, already the small sample of only 3 test subjects shows consistency. A more detailed analysis with more subjects and psychometric functions will allow to further detail the threshold findings.

One observable effect, however, is apparent in the body-mount configuration data-set with the vest, which seems to make detection of small stiffness differences in space harder. Two of the subjects, when asked during protocol conduct on ISS, reported that the body-vest caused some additional compliance ("sway") in the experiment, which made the stiffness identification much harder in space. This could be due to a sub-optimal design of the vest brace, not having sufficiently well located supporting points on the operator torso. Results show that a rigid support for this task is better. The wall-mount conduct shows no alteration in space compared to ground. The reaction forces imparted to a crew member during this task, however, caused some 'fatigue' in the lower body as reported by one crew member during space-to-ground communication.

## 7 Conclusion

Stiffness discrimination thresholds in wall-mount configuration show no variation between ground and measurement in space, after long exposure to the space environment. The detection threshold lies between 5–15 % of the 1 Nm/deg. base stimulus level, equalling a threshold of approximately 0.1 Nm/deg. or when expressed as a linear stiffness, approximately 0.9 N/mm (the grip centre point lies 0.113 m from the joint centre). The vest-mount configuration tested in this experiment causes a worsening of the stiffness discrimination threshold to 15–25 % of the base stimulus level in space, likely caused by sway in the mechanical attachment of the body vest. Overall, no deterioration of stiffness detection thresholds can be observed between space and ground for the combined data, if the astronauts are exposed and adjust to 3 months in the microgravity environment.

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