Beyond Astronaut's Capabilities: The Current State Of The Art

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***Abstract*— Space agencies have developed extensive expertise with sustaining human presence in low earth orbits and micro-gravity. Prolonged human presence in space beyond EarthâĂŹs orbit presents additional, some still unsolved issues. These are linked to the distance to Earth (impossibility of effective tele-operation, psychological effects linked to remoteness from Earth, required autonomy, the handling of emergencies, long mission durations), and to the environments beyond the Earth magnetosphere (radiation levels, local environments including atmospheres, dust, gravity, day-night cycles). These issues have impacts on the spacecraft design, the mission operations, astronaut selection and preparation and required supporting/enabling technologies.**

This paper builds upon previous work by Rossini et al. , in critically reviewing and updating the current state of scientific research on enhancing astronaut's capabilities to face some of these challenges [1]. In particular, it discusses the pertinence and feasibility of two approaches aiming at enhancing the chances of success of human missions: induced hibernation state and brain-machine interfaces.

I. INTRODUCTION

A sustained presence in space and the extension of human frontiers is one of the strategic goals of space agencies, as expressed within the frame of the "International Space Exploration Coordination Group", a voluntary, non-binding coordination mechanism among all major space agencies worldwide [2]. While robotic missions have explored already most planets of the solar system, the Apollo programme was the last to see humans venturing beyond low Earth orbits. Human exploration beyond low Earth orbit adds additional constraints and requirements not currently present in human spaceflight and thus opens up new challenges and research directions. In 2013, space agencies worldwide have published an analysis of identified 'Strategic Knowledge Gaps' associated with future human destinations. This list, grouped by areas of knowledge for each destination and prioritised on the basis of crew/mission risks, relevance to mission scenario, and applicability to more than one destination also contains key knowledge gaps related to the human aspect of exploration missions [3]. A 2014 workshop specifically highlighted the limited understanding of the effects of sex and gender to the adaptation to space, providing at the same time a synthetic overview of the state of the art of scientific understanding of key human health issues linked to spaceflight including cardiovascular alterations [4], immune system aspects [5], effects on the neurosensory systems [6], musculoskeletal health [7], reproductive health [8] and behavioural health [9].

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In 2006, Rossini et al. assessed the potential contributions of three specific technical mechanisms to 'enhance' astronauts capabilities [1]. The present paper updates this assessment based on progress made since 2006. In particular, Rossini et al. assessed the technological and scientific pertinence of induced hypometabolic state, brain-machine interfaces and liquid ventilation. While on the first two concepts, substantial progress has been made, research on the latter one does not warrant an updated assessment and will therefore not be discussed.

II. INDUCED HIBERNATION STATE

A. Motivation

In space, humans have to deal with new and extreme environmental conditions which lead to several psychological and physiological issues [10]. From a physiological point of view, microgravity affects the afferent flow in the central nervous system (CNS), causing hypokinesia and a loss of cardiopulmonary performance and circadian rhythms [11]. Without the Earth's magnetosphere protective shielding, astronauts will be exposed to higher radiation levels [12]. Prolonged isolation affects body weight, blood volume, the immune system and the regulation of the hormones rennin and aldosterone [13]. Also psychological factors need to be considered [14]. While astronauts in space stations orbiting the Earth can benefit from daily psychological support and regular contacts with family and friends, communication with operation control and personal contacts on Earth would be substantially different on an interplanetary mission (transmission delays, trajectory related direct communication challenges etc.)[15]. Mass will be one of the main constraints for human missions beyond Earth orbit, resulting in severe limitations for life support systems, water and food usage. Dysdale estimated the total mass for these to be about 40% of the total wet mass for a 2-year mission [16].

Human 'hibernation' has been suggested as one mechanism to deal with many of these issues. Putting astronauts into a hypometabolic stasis could reduce the psychological effects of isolation, reduce the physiological effects of weightlessness and radiation and reduce oxygen, water and food consumption [17] and thus cost of such missions.

B. Natural torpor

Hibernation is a key survival feature of several warm blooded animals including mammals, which hibernate in order to minimise energy consumption during times of reduced activity and food availability, i.e. winter [18]. In this way, they may suppress their metabolic rate by as much as 99% [19]. During hibernation, torpor states are periodically

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interrupted by arousals, during which animals raise again normothermia ('hibernation bout'). The number of bouts during a hibernation season is highly variable, ranging from 10 to 20. There is significant scientific evidence that it is possible to induce torpor in non-naturally hibernating mammals and eventually also humans. Many different animals, including mammals, show the aptitude to use torpor if needed, and no enabling genes or other unique enabling factors for torpor have so far been identified. Torpor and thus hibernation seems to be regulated by mechanisms also responsible or linked to the control of metabolic rates, food intake and biorhythm [19]. Low body temperature is a consequence of reduced metabolic heat production [19], but some animals enter torpor even at high ambient temperatures [20]. During hibernation, physiological functions are altered, reduced or suspended like the heart rate, respiration rate, renal functions, immune system and digestion system [21]. The endocrine regulation of this phenomenon is still unclear but at the intracellular level the suppression of metabolic functions may be achieved via protein phosphorylation of metabolic enzymes, protein synthesis translation factors and ion pumps [19].

C. Induced torpor

Recently attempts have been made to understand the extracellular and intracellular signals that trigger metabolic suppression, and to artificially induce entrance into torpor using metabolic inhibitors.

Since the latest assessment made by Rossini et al., the understanding of hibernation mechanisms has progressed substantially in the areas of natural biomolecules capable of inducing torpor in non-hibernators. While the only previously known way to induce torpor was the use of DADLE, a synthetic compound [22], other natural molecules have been discovered, having the same effect, in particular 2-deoxiglucose, hydrogen sulfide (H_2S) [23] and 5'-AMP [24].

The first two are both metabolic inhibitors but they are toxic to mammals because they disrupt the ATP-production by oxidative phosphorylation [25], compromising the control of the metabolic rate of the major organs. The latter one (5âĂŹ-AMP) has also shown to induce hypometabolism in non-hibernating mammals [25], without this kind of toxicity. Preliminary results indicate that administration of 5'-AMP induces torpor in non-hibernating mammals with a faster kinetics than in natural torpor. Moreover, 5'-AMP also inhibits thermo-regulation and would therefore requires an additional temperature regulation mechanism [24], [25].

D. Side effects and open questions

Despite substantial progress in understanding the pathways for artificially inducing torpor in non-hibernating mammals, progress still needs to be made before considering applying such techniques to humans. This involves particularly a better understanding of a large number of cellular readjustments. Recent research has also changed the understanding of the function of regular arousals. It is assumed that arousals serve critical functions, because the energy required for arousals is estimated to represent up to 90% of the total energy spent during hibernation. Heldmaier has suggested that arousals allow for the repair of neuronal damage induced by prolonged hypo-metabolism and brain inactivity at low temperature [26]. Sleep has been proposed as one of the major reasons for arousals, during which hibernators show to recover from sleep deprivation accumulated during torpor [27]. On the other hand, some animals like black bears and lemurs, do not show arousals, but have a repeated oscillation of body temperature [26]. A better understanding of the function of these arousals seems essential before considering inducing torpor in humans.

E. Conclusions

Substantial progress has been made recently in understanding mechanisms governing hibernation. These indicate the possibility to induce torpor in non-naturally hibernating mammals and eventually humans. Contrary to the conclusions from 2006, the progress made since the assessment by Rossini et al. now allow conceiving a scientifically solid research plan towards the goal of enabling human hibernation as an option to address some of the open issues with long-distance human spaceflight.

III. BRAIN MACHINE INTERFACES ("BMI")

A. Motivations

Human motor performances remain an issue during long-duration human space missions. Movements and perceptions are indeed related to the identification of the gravity axe and therefore a situation of annihilated gravity, negatively affects the performance of the sensory-motor system [10]. Some technological solutions such as robotic arms could benefit from being implemented through a BMI because it could allow the astronauts to do several contemporary actions, for example, while letting him free to use his hands for doing something else. This would result in a great advantage in human motor performances.

B. Advances in brain machine interfaces for human spaceflight

In general, a human-machine interface is a closed-loop system composed of: signal acquisition, pre-processing, feature extraction, classification, application interface, and feedback. It can be a 1. natural interface or a 2. brain-machine interface (BMI), depending on whether the controlling signal is a natural human action or the brain activity. Natural interfaces typically exploit speech recognition, gesture recognition, facial expression recognition, and gaze tracking [28]. BMIs record neural activities at the cortical level by an invasive or non-invasive system. They are then decoded into the intended message/command and connected to actuators. *Invasive* systems directly record the electrical activity of a group of few neurons via electrodes inserted in the user's brain cortex [29]. *Non-invasive* BMI systems use techniques such as electro-encephalogram (EEG), magneto-encephalogram (MEG), functional magnetic resonance (fMRI), positron emission tomography (PET), single-photon emission-computed tomography (SPECT) and near infrared spectroscopy (NIRS), or combining two or more of these in hybrid interfaces [30]. fMRI, PET and SPECT are characterised by a poor temporal resolution and thus not suitable for real-time operations. NIRS has currently low spatial resolution, but also many advantages (non-invasiveness, portability, low cost) that make it interesting for future research. MEG has a better spatial resolution, but it is still unpractical due to high costs and non-portability, leaving EEG as the most suitable choice for most considerations of BMI in space. Advances in this field have mostly been driven by the need of new medical applications for assistive care, resulting in the development of solutions for communication, like P300 spellers [31] and locomotion, like robotic wheelchairs and robotic exoskeletons [32], the latter being of interest for application in space domain (e.g. MINDWALKER project) [33]–[36]. Recently, ESA has developed a human arm exoskeleton aimed at enabling inspace force-feedback telemanipulation [37]. Besides the advances in the hardware, also to the development of new classification algorithms, benefiting from advances in artificial intelligence [38] is playing an important role. In parallel, BMI applications are introduced in entertainment products targeting the general public [39]–[41].

Despite these advances in BMI technology, many challenges remain to employing BMI for human spaceflight tasks, including low information transfer rates [42]. This depends on the number of selections per minute, the number of possible choices and the probability of detection of the desired choice [43]. Rates are still in the range from 5 to 25 bits/min. Moreover, extensive training time for users is needed, and also the issue of possible changes in the user's brain activity remains, due to fatigue or distractions. This can lead to significant decrease of performances [44]. Concerning the issue of transfer rate, a new collaborative form of BMI was recently tested, namely combining brain activity of several users involved in the same activity and therefore accelerating the transfer rate. This resulted in achieving a simulation success in 67.5% of the cases [45]. Nevertheless, an efficient BMI for human spaceflight would require much higher success rates.

C. Virtual reality, a new possibility

A new promising field in the direction of augmenting astronauts' capabilities is constituted by virtual reality (VR), computer generated environments that can simulate places in the real or imaginary world [46]. It has proven to be a powerful tool for ground-based training of astronauts for extravehicular activity (EVA), for operational processes for which a proper ground-based training is not sufficient due to physical constraints, and for assessing task feasibility [46]. VR was used for the first time in an operational context in 1993, for the repair mission of the Hubble Space Telescope [47]. Recently VR has started to be enriched by the possibility of virtually sensing through haptic technology, which provides the user tactile feedback [48], so the next logical step is the integration of BMI and VR for human spaceflight. It has been recently shown that VR-based feedback particularly improves the users' performance compared to simple 2D feedback [49]. A proposed explanation is that VR increases the user's motivation level [50].

D. Conclusions

Brain machine interfaces have substantially improved since 2006, especially regarding greater availability of the technology and the development of classification algorithms based on artificial intelligence. Current research efforts are focusing on consumer electronics, medical and therapeutic needs, with relatively little attention to applications for human spaceflight. Expected progress in BMI technologies for consumer and entertainment electronics would enable future applications for human spaceflight. It is therefore important to monitor the progress for an early identification of opportunities and eventually direct research via delta-development towards areas of interest for human spaceflight. A substantial improvement of BCI performances would allow astronauts to increase the number and the quality of feasible operations, but this would require a significantly higher information transfer rate.

IV. CONCLUSIONS

Much progress has been made since the 2006 assessment, both on understanding hibernation and on brain machine interfaces. For the former, induction of hibernation has been achieved in non-naturally hibernators mammals, with molecules that are naturally occurring in the body. Although several issues still need to be addressed, current knowledge allows already for a targeted research plan. Substantial knowledge growth is expected due to the growing medical interest in this topic. For the latter, BMIs are not yet ready for an operational deployment to enhance astronaut capabilities, but progress on developing virtual reality technologies is expected to lead to new possibilities for applications for human spaceflight.

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