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Ergonomic constraints for astronauts: challenges and opportunities today and for the future

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ABSTRACT

Manned spaceflight is ergonomically constrained by living and working in a confined space in microgravity where astronauts on both short and long duration missions are exposed to daily radiation levels well above those received on Earth. Living in microgravity, especially on long duration missions aboard the International Space Station has deleterious physiological and psychological effects on astronaut health and astronauts may on just one mission receive exposure to a cumulative radiation dose normally received in a lifetime on Earth. It is unrealistic at present to contemplate continuous missions of greater than 1 year, and to mitigate against current ergonomic constraints, space agencies have outlined roadmaps to introduce artificial gravity and develop strategies for conferring human resistance to radiation. In parallel, the concept of whole brain emulation (WBE) and 'uploading' of human consciousness on to a platform within the rapidly growing field of artificial intelligence is one scenario which may remove the future requirement for a physical crew.   This paper highlights incidents and accidents which have resulted in astronaut injury because of ergonomics in space, considers the timing of deployment of technology roadmaps and draws together multi-disciplinary fields to project a future whereby deep space travel may be manned by an e-crew, devoid of many of the established ergonomic boundaries that apply to human astronauts.

KEYWORDS

Microgravity, radiation, habitat confinement, artificial intelligence

Objectives

The objectives of this paper were to review the three principle ergonomic constraints for astronauts undergoing space travel, describe how environmental adaptation may relieve these constraints and illustrate some opportunities for future space exploration based on either human crew or an e-crew of human avatars which utilise developing concepts in artificial intelligence.

Introduction

The scope of this paper was to consider the principle ergonomic constraints of living and working in space. Spacecraft ergonomics are constrained by three factors which impact the daily lives of astronauts. These are a). microgravity, b). space radiation and c). habitat confinement and they present considerable ergonomic challenges for future travel, which includes preparing for deep space exploration and colonisation (DSEC).

Such is the requirement to mitigate against the effects of microgravity and damage caused by radiation the National Aeronautics and Space Administration (NASA), Ames institute with input from space agencies from Europe and Japan and leading worldwide academics have developed a roadmap for artificial gravity (AG) and radioprotection research (Clement, 2017, Cortese et al., 2018).

Mitigation counter-measures for the above constraints would not be needed to the same degree, if at all, if the crew was not a physical astronaut-based crew, but comprised a virtual e-crew based upon human avatars. Remarkable advances in the fields of machine-based learning artificial intelligence (AI) lead us to the possibility that a virtual or e-crew of hybrid human-computer avatars could be a future generation of deep space travellers. The integration of an avatar-based e-crew with nano spacecraft such as the StarChip (Lubin, 2015) bypasses all the issues associated with physical human space travel, while retaining the ability to travel for decades or centuries.

This paper will draw together key and very recent findings from multiple disciplines in life sciences, engineering and computational biology. We will present two simplistic scenarios, the major challenges associated with habitat ergonomics in space and some opportunities for both space and terrestrial science development which may have implications for human health and our current understanding of human civilisation.

Methods

We systematically searched the BIOSIS, MEDLINE, PUBMED and EMBASE databases to identify reports and manuscripts published between January 2003 and September 2018 that addressed the effects of space craft ergonomics and incidents which may affect astronaut health. To provide a future looking context we also performed a search for scientific literature supporting risk-reduced astronaut based deep space exploration and colonisation (DSEC) and DSEC based upon human avatars. Relevant data from non-clinical trials and human observational studies were abstracted and presented descriptively.

Results

Incidents in spaceflight

An invaluable tool with open public access describes the significant incidents in human spaceflight (https://spaceflight.nasa.gov/outreach/SignificantIncidents/index.html). This includes loss of crew, crew injury or illness and loss of vehicle or the mission. Despite the high risks to astronauts associated with spaceflight, the incidents which have caused injuries induced by habitat ergonomics are restricted primarily to musculoskeletal injury and space adaptation back pain (SABP) (Ramachandran et al., 2018), impact injury and one report of an eye injury from a strap on an exercise machine. Table 1 summarises the incidents which have resulted in injury to one or more astronauts. In addition to date, 219 in-flight musculoskeletal injuries have been reported on the ISS of which 198 are in men and 21 in women (Scheuring et al., 2009, Ramachandran et al., 2018). No in-flight musculoskeletal injury to date has caused a failure of mission objectives, and the majority of injuries have been caused by crew activity in the spacecraft cabin such as transiting between modules, aerobic and resistive exercise and injuries caused by the extravehicular activity (EVA) suit components such as abrasions and small lacerations to the hand. SABP is frequently reported by astronauts during the early phase of space flight as they adapt to microgravity. The incidence of SABP among astronauts was 52%, 86% of which reported mild pain, 11% moderate pain and 3% severe pain. The most effective treatments were bending the knees to the chest, stretching the lumbar spine the use of analgesics and exercise (Scheuring, 2012).

Table 1. Astronaut-reported incidents reported during space missions as a consequence of spacecraft ergonomics

Incident	Mission	Date	Event	Citation
Spacesuit design fault	Voskhod 2	18th March 1965	Space suit inflation after EVA prevented re-entry. Manual air-bleed resulted in the bends. Life-threatening	Rincon (2014)
Equipment strike during splashdown	Apollo 12	24th November 1969	Astronaut struck by a camera which broke free from storage resulting in concussion and cut above the eyebrow requiring stitches. Not life threatening.	Crotts (2014)
Spacesuit puncture	Space shuttle STS-37	8th April 1991	Penetration of glove by a palm bar during an EVA. Abrasion to right index finger, not life-threatening.	Fricke (1991)
Eye injury from exercise equipment	Mir	28t May 1995	Elastic strap of exercise machine flew up and hit the right eye. Eye drops provided and eye healed. Not life-threatening.	NASA-1 (2011)
Shoulder injury	Soyuz TMA-1	3rd May 2003	Ballistic re-entry (8-9G) of return from ISS. Astronauts encountered hard lining and one sustained a shoulder injury. Not life-threatening.	Watson (2003)
Water leak in space suit	ISS expedition 36	16th July 2013	Water leaking into helmet during an EVA. EVA aborted. Rapid response resulted in not life-threatening situation.	Harding (2013)

Many of incidents reported above could be completely mitigated by the introduction of simulated gravity, best known as artificial gravity (AG). Although the concept of AG was formulated over a century ago (Tsiolkovsky, 1903, Hall, 2016), it has only recently been shown to reduce effects on muscle and bone mass in a rodent model study undertaken by the Japanese Space Agency on board the ISS (Shiba et al., 2017). Many non-clinical *in vitro* and *in vivo* studies will need to be conducted in both animal and plant models, together with human studies in simulated microgravity on Earth before deployment of a system capable of generating AG in space can be tested and validated as a robust and reliable countermeasure. The roadmap described above outlines a series of studies which should see the deployment of space borne AG systems in the mid to late 2020s.

An outline of two potential scenarios supporting DSEC

Although countermeasures to better support human-based DSEC are being considered, it is appropriate to consider in parallel the possibilities for DSEC to be conducted by an e-crew of human avatars. Figure 1 is a Mindmap diagram of two potential scenarios which considers both astronaut and avatar-based DSEC. For both scenarios, it will be essential to thoroughly understand the risks involved and devise mitigation strategies with tested employable countermeasures in terrestrial analogues of space exploration.

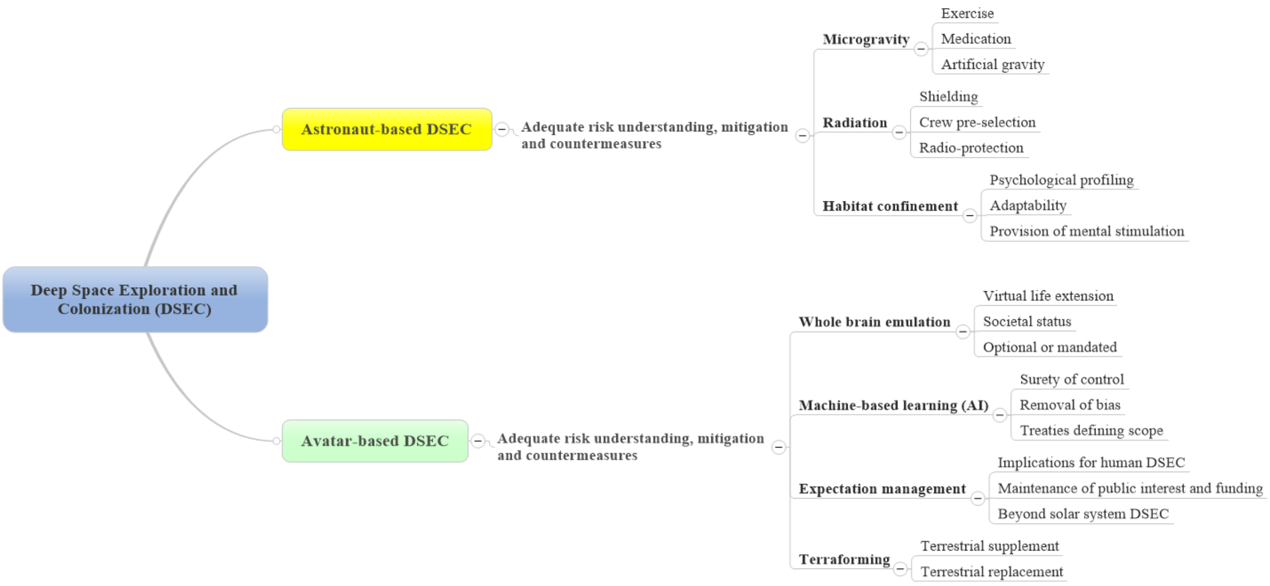

Figure 1. Mind map showing two possible scenarios supporting deep space exploration and colonisation (DSEC). Deployment of astronaut and avatar-based DSEC is subject to understanding of risk mitigation and activation of appropriate countermeasures.

Table 2A (astronaut-based DSEC) and Table 2B (avatar-based DSEC) collate selected and summarising supporting scientific literature for each of the sub-topics shown in Figure 1 and illustrate some of the challenges and opportunities for each theme. Selected citations are provided.

Table 2A. Key observations from supporting scientific literature underpinning three identified topics for astronaut-based DSEC

Topic	Sub-topic	Key observations	Citation
Microgravity	Exercise	Astronauts typically undergo aerobic and resistance exercise for 2-3 hours per day.	Braddock (2018)
	Medication	Anti-osteoporotic agents may prevent bone loss and other candidate drugs are and continue to be evaluated in animal models on the ISS.	Braddock (2017), Braddock (2019)
	AG	Attenuates tissue atrophy in mice on the ISS.	Shiba et al. (2017)
Radiation	Shielding	Shielding is not feasible, mission duration will be limited to < 3 years.	Chancellor (2018)
	Crew selection	No studies have been conducted supporting	N/A

		natural human resistance to radiation.	
	Radioprotection	Radio-resistance factors isolated from extremophiles shown to be radio-protective in human and mouse cells.	Cortese et al. (2018)
Confinement	Psychology	NASA screening and training selection program is 3 – 4 years duration.	NASA (2017)
	Adaptability	Provision of training for conflict management, leadership skills, cultural awareness	NASA (2017)
	Stimulation	Provision of structured Earth-based and in-flight support care package.	Czeisler & Barger (2017)

Table 2B. Key observations from supporting scientific literature underpinning four identified topics for avatar-based DSEC

Topic	Sub-topic	Key observations or questions	Citation
Whole brain emulation	Virtual life extension	Concept may remove the anxiety of death and the motivation behind achieving the best from a physical life.	Linssen & Lemmens (2016)
	Societal status	Does a virtual individual with a human consciousness have the same rights and privileges in society?	Serruya (2017)
	Optional/mandated	If WBE is possible, who will decide on the emulation process?	N/A
Machine-based learning (AI)	Surety of control	Security and control is essential and identified as a clear risk at the outset. Maintenance of human control is essential.	Tegmark (2017), Rees (2018)
	Removal of bias	Prejudice has been detected as a consequence of indirect reciprocity. Monitoring steps will need to be taken to eliminate this facet of AI.	Whitaker et al. (2018)
	Treaties defining scope	A unifying global roadmap for defining the scope of AI is needed across all disciplines. Space agencies including NASA and ESA have developed project teams to exploit AI in space research.	Tegmark (2017), Rees (2018)
Expectation management	Implications for human DSEC	Manned spaceflight and colonisation of Mars is an expectation. Colonisation beyond Mars may be a viable and publicly acceptable facet for avatar-based DESC	N/A
	Maintenance of public interest and funding	Essential to maintain interest and opportunities for scientific research in human DSEC. Space agency agendas will require careful co-ordination and	N/A

		communication.	
	Beyond solar system DSEC	Fully automated or avatar based DSEC may be applicable to asteroid, comet and mining of non-terraformed planets. Concepts yet to develop.	N/A
Terraforming	Supplemental	The concept of asteroid and cometary mining has been proposed and the requirement for partial or full terra-formation is in its infancy.	N/A
	Replacement	Recent data suggests the CO_2 inventory on Mars is insufficient to support generation of an atmosphere to warm the planet.	Jakowsky & Edwards (2018)

Discussion

Observations supporting avatar-based DSEC are not well defined. Progress in whole brain emulation research, if successful, will have profound effects on human civilization. The pace of technological development for machine-based learning AI should be tempered with caution (Parasumaran et al., 2000, Russell et al., 2015, Tegmark, 2017, Rees, 2018) and warrants a global approach to agree on scope, primarily subject areas which are *out* of scope. For space exploration, space agencies have adopted collaborative approaches which, subject to feasibility, will start to lay the foundation for integration with WBE technology.

Both scenarios presented are not mutually exclusive and manned space exploration has a secure place in science as despite advances in automation and future looking plans for developing AI, fully autonomous robotic automation, let alone that which has the capacity for human thought, remains a distant ambition. In addition, DSEC within the solar system either is or will be within the capabilities of human limitations and the emotive sense of achievement and its communication is both a necessary and powerful tool to maintain public interest in space travel. However, it may be envisaged that such new technology may lead to chatbots created from a person's digital data legacy which could enable the creation of a digital person, an augmented eternity which will continue to have awareness of current events and formulate opinions via artificial neural networks (Simonite, 2017, Mater, 2017). Although the terrestrial consequences for human society are very profound indeed, this technology may present an excellent application for DSEC and provide ample opportunity for an avatar e-crew to demonstrate the ability to manage unforeseen and inevitable issues which will accompany deep space travel. Perhaps one may predict that an avatar e-crew is the scouting mission to distant worlds and when a candidate habitable exoplanet has been identified capable of supporting life (Kiang et al., 2018), the scientific challenge of human travel and colonisation will provide the sole focus for humankind.

Although it may be argued that finding solutions to man-made Earth related problems is both a better use of resources and should precede extra-terrestrial colonisation, in our view we believe that human kind will settle on worlds other than Earth. The irrepressible quest for scientific exploration, advances in automation technology (Campa et al., 2019) coupled with the finite resources of Earth, an ever-expanding and ageing population and the belief amongst many climatologists and ecologists that human activity has triggered the Holocene extinction event (Pimm et al., 2014, Ceballos et al.,

2015) will drive forward DSEC. At first sight, it is attractive to consider the heroics of manned space missions, the staggering achievement of leaving the Earth's gravity and now, 50 years ago landing astronauts on the Moon and returning them to Earth. However, DSEC is limited by human frailty and the longevity of the human lifespan, at least today, to exploring and colonising celestial bodies within our Solar system. The possibility to propel nano spacecraft with an onboard e-crew of human avatars for 10s, 100s and even 1000 year voyages to explore other solar systems is not yet scientific fact. Neither is it scientific fantasy.

Said Konstantin Tsiolkovsky (1857-1935), a Russian scientist and pioneer of the astronautic theory supporting all modern rocketry:

> *"The Earth is the cradle of humanity, but mankind cannot stay in the cradle forever."*

References

Braddock, M. (2017). Ergonomic challenges for astronauts during space travel and the need for space medicine. Journal of Ergonomics 7: 221.

Braddock, M. (2018). Exercise and ergonomics on the International Space Station and Orion spacecraft. Journal of Ergonomics Research 1: 2.

Braddock, M. (2019). From drug discovery to drug development using the microgravity assist. Current Drug Discovery Technologies 16: 1, doi:10.2174/1570163816666190112150014.

Campa, R., Szocik, K. & Braddock, M. (2019). Why space colonisation will be fully automated. Technological Forecasting and Social Change (manuscript accepted).

Ceballos, G., Ehrlich, P.R., Barnowsky, A.D., Garcia, A., Pringle, R.M., & Palmer, T.M. (2015). Accelerated modern human-induced losses: entering the sixth mass extinction. Scientific Advances 1:e1400253.

Chancellor, J.C., Blue, R.S., Cangel, K.A., Aunon-Chancellor, S.M., Rubins, K.H., Katzgraber, H.G., & Kennedy, A.R. (2018). Limitation in predicting the space radiation health risk for exploration astronauts. NPJ Micrograviaty 4: 8.

Clement, G. (2017). International roadmap for artificial gravity research. npj Microgravity 3:29 doi:10.1038/s41526-017-0034-8.

Cortese, F., Klokov, D., Osipov, A., Stefaniak, J., Mokalev, A., Schastnaya, J., Cantor, C., Aliper, A., Mamoshina, P., Ushakov, I., Sapetsky, A., Vanhaelen, Q., Alchinova, I., Karganov, M., Kovalchuk, O., Wilkins, R., Shtemberg, A., Morcels, M., Bastout, S., Izumchenko, E., Pedro de Magalhaes, J., Artemov, A.V., Costes, S.V., Beheshti, A., Mao, X.W., Pecaut, M.J., Kaminsky, D., Ozerov, I.V., Scheibye-Knudsen, M., & Zhavoronokov, A. (2018). Viv la radioresistance!: converging research in radiobiology and biogerontology to enhance human radioresistance for deep space exploration and colonisation. Oncotarget 9: 24461.

Crotts, A. (2014). The new Moon: water, exploration, and future habitation. Cambridge University Press. P356 ISBN 978113991557.

Czeisler, C.A. & Barger, L.K. (2017). Sleep-awake actigraphy and light exposure during spaceflight-long. Retrieved on October 16th 2018 from https://www.nasa.gov.mission_pages/station/research/experiments/294.html.

Fricke, R.W. (1991). STS-37 space shuttle missions report May 1991. NASA-CR-193062. Extravehicular activity evaluation, p16. Retrieved on October 17th 2018 from htpps://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930016767.pdf.

Hall, T.W. (2016). Artificial gravity in theory and in practice. 46th International Conference on Environmental Systems ICES-2016-194, Vienna, Austria.

Harding, P. (2013). EVA-23 terminated due to Parmitano EMU issue. NASA Spaceflight, July 16th 2013.

Jakowsky, B.M., & Edwards, C.S. (2018). Inventory of CO_2 available for terraforming Mars. Nature Astronomy 2: 634.

Kiang, N.Y., Domagal-Goldman, S., Parenteau, M.N., Catling, D.C., Fujii, Y., Meadows, V.S., Schwieterman, E.W., & Walker, S.I. (2018). Exoplanet biosignatures: at the dawn of a new era of planetary observations. Astrobiology 6: 619-629.

Linssen, C., Lemmens, P. (2016). Embodiment in whole-brain emulation and its implications for death anxiety. Journal of Evolution and Technology 26: 1-15.

Lubin, P. (2015). A roadmap to interstellar flight. Journal of the British Interplanetary Society 69: 2.

Mater, A. (2017). Beyond the grave. New technology is forcing us to confront the ethics of bringing people back from the dead. Retrieved on October 17th 2018 from htpps://qz.com/896207/death-technology-will-allow-grieving-people-to-bring-back-their-loved-ones-from-the-dead-digitally.

NASA (2017). International space station medical monitoring. Retrieved on October 17th from htpps://www.nasa.gov/mission_pages/station/research/experiments/1025.html.

NASA-1 (1995). Norm Thagard: An ending and a beginning. Retrieved on October 17th 2018 from htpps://history.nasa.gov.SP-4225/nasa1/nasa1.html.

Parasumaran, R., Sheridan, T.B., & Wickens, C.D. (2000). Systems, man and cybernetics. Part A: systems and humans IEEE Transactions 30: 286-297.

Pimm, S.L., Jenkins, C.N., Abell, R., Brooks, T.M., Gittleman, J.L., Joppa, L.N., Raven, P.H., Roberts, C.M. & Sexton, J.O. (2014). The biodiversity of species and their rates of extinction, distribution and protection. Science 344: doi.org/10.1126/science.1246752.

Ramachandran, V., Dalal, S., Scheuring, R.A., & Jones, J.A. (2018). Musculoskeletal injuries in astronauts: review of pre-flight, in-flight, post-flight and extravehicular activity injuries. Current Pathology Reports 6: 149-158.

Rees, M. 2018. On the future prospects for humanity. Princeton University Press.

Rincon, P. (2014). The first spacewalk. How the first human to take steps in outer space nearly didn't return to Earth. Retrieved on October 17th 2018 from htpps://www.bbc.co.uk/news/special/2014/newspec_9035/index.html.

Russell, S., Dewey, D., & Tegmark, M. (2016). Research priorities for robust and beneficial artificial intelligence. arXiv: 1602.03506v1.

Scheuring, R.A., Mathers, C.H., Jones, J.A., & Wear, M.L. (2009). Musculoskeletal injuries and minor trauma in space: incidence and injury mechanisms in U.S. astronauts. Aviation and Space Environmental Medicine 80: 117-124.

Scheuring, R. (2012). Space adaptation back pain: a retrospective study. Aviation Space & Environmental Medicine 83: 2-7.

Serruya, D. (2017). Connecting the brain to itself through emulation. Frontiers in Neuroscience 11: 373.

Shiba, D., Mizuno, H., Yumoto, A., Shimomura, M., Kobayashi, H., Morita, H., Shimbo, M., Hamada, M., Kuso, T., Shinohara, M., Asahara, H., Shirakawa, M., & Takahashi, S. (2017).

Development of a new experimental platform 'MARS' – multiple artificial-gravity research system to elucidate the impacts of micro/partial gravity on mice. Scientific Reports 7: 10837.

Simonite, T. (2017). Intelligent machines. Facebook's perfect impossible chatbot. Retrieved on October 16th 2018 from htpps:// www.technologyreview.com/s/604117/facebooks-perfect-impossible-chatbot/.

Tegmark, M. (2017). Life 3.0. Being human in the age of artificial intelligence. Penguin press ISBN 9780141981802.

Tsiolkovsky, K.E. (1903) The exploration of cosmic space by means of reaction devices (translated from Russian). The Science Review.

Watson, T. (2013). Soyuz misses its mark but still finds Earth safely. Retrieved on October 17th 2018 from htpps://usatoday30.usatoday.com/news/wprld/2003-05-03-space-shuttle_x.html.

Whitaker, R.M., Colombo, G.B., & Rand, D.G. (2018). Indirect reciprocity and the evolution of prejudicial groups. Scientific Reports 8: 13247.