ABSTRACT Moon colonization has been within our capabilities since the Apollo era. Even though technology maturation has increased this capability and decreased the cost for private firms to potentially colonize the Moon, this has not been developed to date. During the Apollo program, lunar surface operational activities were limited due to luminescence and reflectance lighting issues, which indicate that human body mobility on the Moon may be restricted during extravehicular activities. We aimed to examine human performance on a simulated Moon environment during extravehicular activities by identifying visual restrictions that can affect body mobility due to the lunar surface. Within an artificial lunar environment we measured walking time of our participants who completed three walking tasks under lunar simulated continuous light, lunar simulated strobe light and normal electricity Earth light. We found mean differences between walking time with all lighting conditions. We conclude that astronauts may have decreased body mobility during extravehicular activities under simulated Moon lighting conditions.

INTRODUCTION For thousands of years, humans have gazed upon the stars wondering what relationship they have to Earth. This fascination has driven humans, kind to study scientific phenomena, to discover our origin, and to determine whether we are the only intelligent species in the Universe. For many centuries, discussions have raged about whether we can live outside of Earth’s atmosphere either in the space environment or on another planet. As far back as 1638, it was predicted that lunar colonization is feasible, and since the 1950s, many concepts for colonization architectures have been studied and suggested. For instance, in 1959 the “Project Horizon” intended to establish a fort on the Moon by 1967. Recently, Japan announced that they plan to send astronauts to the Moon by 2020 to start construction of a base, which will be completed by 2030. Similarly, Russia plans to create a Moon base by 2032. Among other suggestions there is evidence that a Moon colony can be built in advance using a glass-like solid structure coated with metal to be protected by radiation in order to extend the colonization period. Also, during a Moon colonization we can test the ability of humans to survive with low gravity and to use the Moon as a facility for space observation.

The goal of Moon colonization is nearly within our reach. While we have the technology for the trip to the Moon, building up the colony habitats and operating in a safe and efficient manner creates a whole new set of challenges to be mastered. During the Apollo program, lunar surface...
We planned a research study to test the effects of lunar lighting conditions and impeded depth perception on human body mobility in a simulated lunar environment. Individuals’ body mobility was examined by measuring walking time through an obstacle course under “lunar-like” conditions. We hypothesized that the lunar simulated lighting conditions and different depth perception will reduce individuals’ body mobility as compared to Earth lighting and depth perception conditions.

AIM OF THE STUDY We planned a research study to test the effects of lunar lighting conditions and impeded depth perception on human body mobility in a simulated lunar environment. Individuals’ body mobility was examined by measuring walking time through an obstacle course under “lunar-like” conditions. We hypothesized that the lunar simulated lighting conditions and different depth perception will reduce individuals’ body mobility as compared to Earth lighting and depth perception conditions.

EXPERIMENTAL DESIGN We created an obstacle course emulating lunar surface conditions in a completely dark room. Both continuous and strobe light of the Fenix TK15 flashlight was adjusted to 400 lumens per square meter for each participant. The room’s electric light was used to simulate the Earth’s lighting conditions as a control situation. The “continuous light” condition represented the luminescence and reflectance lighting issues that Apollo astronauts came across on the lunar surface. While the “strobe light” condition represented the backscatter conditions of the lunar surface. Finally, we used

We anticipate that in order to create a Moon colony, human body mobility and vision on the Moon’s surface should be examined in advance. Humanity aims to improve and keep humans’ health in high standards. Spin-off technology has helped to develop devices that are essential for diagnosis and treatment. As such, given a possible colonization of the Moon we may take advantage of technology that would be developed for this purpose.

RESULTS

RATIONALE FOR THE STUDY Human body mobility and vision are key elements for human life. This paper aims to address the aspect of human body mobility on a simulated Moon environment by identifying the combination of visual and body mobility restrictions due to the lunar surface (rocks and craters). This may direct future research in the area that could develop spin-off technology that may benefit human health on Earth and/or predict health problems during a colonization of the Moon.
as an “Earth light” condition a normal lighting room given that our aim was to compare Earth’s conditions with simulated Moon conditions. Each participant wore a pair of seeing glasses (PICTURE 1) that underestimated depth perception simulating the space environment only during the “continuous light” and “strobe light” conditions. In the initial phase, one investigator measured the distance difference, by using a tape measure, between seeing an object with and without wearing the seeing glasses to determine the depth perception that the seeing glasses caused (approximately one meter). Additionally, the participants reported that they were free from visual, vestibular and body disabilities; however, their eyesight was not assessed. All participants used the same pair of seeing glasses.

Each participant had to complete three walking tasks on the artificial surface in three different lighting conditions – “continuous light” and “strobe light” simulating lunar lighting conditions within a dark room as well as “normal Earth light” under the room’s 60 watt bulbs simulating Earth’s lighting condition. During the “normal light” condition walking task, the participants wore neither the flashlight nor the seeing glasses. The weight of the flashlight was 207.2 g including headgear and batteries. The participants were asked if the headgear and flashlight caused any discomfort that would prevent them to walk normally independently of the lighting conditions. No discomfort or navigation problems were reported from the participants. We measured walking time from a sitting (start) to a sitting (stop) position during each task. There was a 5-minute break between each walking task to ensure the eye adaptation from darkness to light. Additionally, we first examined the “continuous light” and “strobe light” conditions that were in the dark room and thereafter we examined the “normal Earth light” condition. Before the experimental runs we instructed every participant to walk normally according to his/her abilities and not to run or jump over the obstacles. We briefly showed them the route under full room electric lighting to familiarize them. An investigator was following each participant in every task to prevent any accident. As a precaution before and after each task, we checked the status of the participants against dizziness, tiredness and discomfort. The participants did not display any problem during the experiment.

REPORTING OF OUTCOMES The baseline characteristics of the participants can be found in Table 1. We identified significant mean differences between performance during simulated “continuous light” lunar condition and performance during simulated “strobe light” lunar condition as well as between performance during simulated “continuous light” lunar condition and performance during “normal Earth light” condition (FIGURE 2). Also, we identified a significant mean difference between performance during simulated “strobe light” lunar condition and normal Earth light condition (FIGURE 2). Finally, the analysis of variance revealed no significant differences in performance between men and women.
We detected a significant positive association between age and performance during simulated “continuous light” lunar condition (FIGURE 3A), as well as a significant positive association between age and performance during simulated “strobe light” lunar condition (FIGURE 3B). Nevertheless, no correlation was detected between age and performance under “normal Earth light” condition. Linear regression analysis revealed that the correlation between age and performance during simulated “continuous light” lunar condition as well as performance during simulated “strobe light” lunar condition persists. The linear regression analysis, however, detected no correlation between age and performance under “normal Earth light” condition. Finally, no correlation was detected between body mass index (BMI) and performance either during simulated “continuous light” lunar condition or during simulated “strobe light” lunar condition.

We also identified a negative association between maximum oxygen uptake (VO₂ max) and age (FIGURE 4A), as well as VO₂ max and BMI (FIGURE 4B). Furthermore, we found a negative association between VO₂ max and performance during simulated “continuous light” lunar condition (FIGURE 4C), as well as performance during simulated “strobe light” lunar condition (FIGURE 4D). No relationship between VO₂ max and performance during “normal Earth light” condition was detected. The linear regression analysis detected an association between VO₂ max and performance during simulated “continuous light” lunar condition as well as performance during simulated “strobe light” lunar condition while no association between VO₂ max and performance during “normal Earth light” condition was detected.

**DISCUSSION** The aim of the present study was to examine the effects of simulated lunar lighting conditions and impeded depth perception on human body mobility in a simulated Moon environment during EVAs. We detected that “continuous light” and “strobe light” simulated lunar conditions may reduce human body mobility on an artificial Moon surface compared to Earth’s conditions. It was observed from the first space missions that astronauts were not likely to observe objects on the Moon that are not exposed to direct sunlight. Also, the reflectance of the lunar surface is characterized by a peaked backscatter in the direction of the source. Backscattering is a reflection of waves, particles, or signals back to the direction from which these waves, particles, or signals came. On Earth the materials are diffuse reflectors while there are some scattering components. Also, in Earth’s atmosphere isotropic illumination can be observed even in shadowed areas. This is completely absent on the Moon, which is why the Apollo astronauts were not likely to observe objects that were not exposed to direct sunlight.

Strobe lights can simulate backscatter, which significantly increases the reaction time to visual stimuli. This is because strobe lights flash up to hundreds of times per second and stop the appearance of motion. Therefore, the simulated “strobe light” lunar condition in our study may have reduced the reaction time of our participants, decreasing their body mobility. Correspondingly, the simulated “continuous light” lunar condition in our experiment in a fully dark room may have caused difficulties similar to those of the “strobe light” condition. The “continuous light” simulation in our study may represent the luminescence and reflectance lighting issues that Apollo astronauts came across on the lunar surface. Indeed, on the lunar surface there is no time for the eye to adjust to the Earthshine in order to observe details on the Moon surface given that the transition across the terminator from the sunlit portion to the Earth lit portion is rapid.

In both “strobe light” and “continuous light” simulated lunar conditions we also used seeing glasses that underestimated...
Human performance under simulated lunar lighting conditions: is it possible to walk on the moon?

Dinas et al.

We found that the simulated lunar lighting conditions along with the simulated depth perception (approximately one meter) reduced the body mobility of our participants in comparison to the normal Earth lighting conditions and depth perception. Regarding depth perception, our findings are in accordance with previous evidence that showed that astronauts underestimate distances in microgravity.12

In our study we did not use a random order of the different lighting conditions to assess the walking time of the participants and therefore, a learning effect might have occurred. A previous task force report of the European Respiratory Society and the American Thoracic Society regarding the 6-minute walking test in patients and healthy individuals reported that more studies are needed to confirm a learning effect phenomenon even though the participants walked the same path on a treadmill.16 In our experiment the lighting and vision conditions were different for each task that was performed by the participants while we have used a familiarization phase for them before the experimental process. In this regard, our participants undertook the obstacle course once before the actual measurements were taken in order to familiarize them with the obstacle course and to minimize the learning effect in their walking performance. Also, a previous study suggested that three walks are needed in the 6-minute walking test in patients and healthy individuals in order to achieve the best performance due to a learning effect in walking.18 Nevertheless, in our study each lighting condition was performed only once, which suggests that it is unlikely for a learning effect to have affected performance in every lighting condition. Furthermore, a previous study examining the performance in a shuttle walking test of patients suffering from chronic airway obstruction reported a learning effect after four identical tests that improved the performance of the participants by 96%.19 While in our study the participants performed three non-identical tasks, with an improvement between the first (continuous light) and second (strobe light) conditions of 9.1% and between the second and third (Earth light) conditions of 30.5%. Furthermore, the fact that we did not detect either a significant correlation or a significant regression between VO2max and “normal Earth light” while we detected a significant correlation and regression between VO2max and both “continuous light” and “strobe light” conditions strongly indicates that the performance of the participants was affected by the Moon simulated lighting and depth perception conditions and not by their ability to walk effectively.

We also found that aging may reduce human body mobility on a simulated Moon surface. Previous research on Earth showed a natural decline in body depth perception to simulate the impeded estimation of distance in microgravity.

Indeed, previous research has shown that walking at different speeds was used to avoid a learning effect phenomenon even though the participants walked the same path on a treadmill. In our experiment the lighting and vision conditions were different for each task that was performed by the participants while we have used a familiarization phase for them before the experimental process. In this regard, our participants undertook the obstacle course once before the actual measurements were taken in order to familiarize them with the obstacle course and to minimize the learning effect in their walking performance. Also, a previous study suggested that three walks are needed in the 6-minute walking test in patients and healthy individuals in order to achieve the best performance due to a learning effect in walking. Nevertheless, in our study each lighting condition was performed only once, which suggests that it is unlikely for a learning effect to have affected performance in every lighting condition. Furthermore, a previous study examining the performance in a shuttle walking test of patients suffering from chronic airway obstruction reported a learning effect after four identical tests that improved the performance of the participants by 96%. While in our study the participants performed three non-identical tasks, with an improvement between the first (continuous light) and second (strobe light) conditions of 9.1% and between the second and third (Earth light) conditions of 30.5%. Furthermore, the fact that we did not detect either a significant correlation or a significant regression between VO2max and “normal Earth light” while we detected a significant correlation and regression between VO2max and both “continuous light” and “strobe light” conditions strongly indicates that the performance of the participants was affected by the Moon simulated lighting and depth perception conditions and not by their ability to walk effectively.

Figure 2 | Mean recorded walking time in three different lighting conditions. Continuous and strobe lights represent lunar simulated conditions. Normal light represents Earth conditions.

* Significant differences between continuous light performance and strobe light performance (p=0.002)
≠ Significant differences between continuous light performance and normal light performance (p=0.001)
¥ Significant differences between strobe light performance and normal light performance (p=0.001)
while older adults during physical actions display different perception of the environment. Additionally, people with poor physical fitness may have lower perceptual judgments. This evidence may well explain our finding that aging may reduce body mobility in a simulated Moon environment during EVAs. Our participants showed no balance problems during the tasks. Nevertheless, previous evidence on Earth showed that older adults may have lower performance due to decline of muscle mass, their mobility and temporary loss of balance. This may also explain the negative correlation we found between age and body mobility in both simulated Moon environments, given that the Moon’s gravity has not been addressed in our experiment. Gravity is a key element of human performance, especially for the function of the musculoskeletal system. Lack of gravity or low gravity may cause a decrease of fat free mass, including cardiac muscle, that may reduce the ability to move and therefore, body mobility. Furthermore, as previously indicated, older adults judged distances as farther than younger adults. This may also have caused further difficulties in our older participants to complete the simulated Moon tasks in our experiment.

We detected an inverse association between VO$_2$max and age as well as between VO$_2$max and BMI, which is in accordance with previous studies. Currently, the minimum requirement of VO$_2$max given by the National Aeronautics and Space Administration (NASA) for participating in a space mission is 32.9 ml kg$^{-1}$ min$^{-1}$, which needs further investigation. The average VO$_2$max for untrained healthy individuals is approximately 35–40 ml kg$^{-1}$ min$^{-1}$ for male and 27–31 ml kg$^{-1}$ min$^{-1}$ for female. Our participants display an average of VO$_2$max 40.47±5.40 ml kg$^{-1}$ min$^{-1}$ for men and 45.81±9.80 ml kg$^{-1}$ min$^{-1}$ for women. These values meet both the VO$_2$max requirements of NASA and the general population VO$_2$max limits for untrained healthy individuals. Given that our results indicate a negative correlation...
between VO<sub>2</sub>max and human body mobility in a simulated Moon environment we reinforce NASA’s suggestion for further development of the standards for assessing body mobility of astronauts. Our study refers only to human performance during EVAs on the Moon. Given that EVAs require space suits against the harmful conditions of space, body mobility would also depend on the mobility and functionality of space suits. Therefore, space suits would further reduce body mobility during EVAs.

Given our findings and also that the future Moon inhabitants would be exposed to this Moon environment for extended periods of time during EVAs, their performance problems may be even worse than the acute effects we examined in the current study. However, Moon inhabitants may improve their body mobility through adaptations that may occur during their stay on the Moon surface. The problem of restricted body mobility can be addressed by using training programs before potential Moon inhabitants move to the Moon. Indeed, learning programs on Earth have shown that the cognitive ability of adults can be significantly improved within six weeks. Also, specific exercise programs can be used to improve the body mobility of potential Moon inhabitants. These two elements, cognitive and physical training, may help future Moon inhabitants to improve their adaptation in order to be able to overcome visual and performance problems. Given the existing evidence regarding physical and cognitive performance, we anticipate that this training period would be no more than 10 weeks, but would depend on age and physical fitness. This estimate is based on previous evidence of human physical and cognitive training under Earth conditions. However, the length of this training period focuses only on physical and cognitive performance and does not take into consideration other aspects such as psychological preparation and technical knowledge that the potential Moon inhabitants should obtain before moving to the Moon.
Dinas of al.

While the artificial Moon environment cannot completely represent the actual Moon environment, many other factors could not be addressed in our experiment. For instance, the shadowed parts of the Moon are very black because of the lack of atmosphere and therefore, this environment could not be perfectly simulated. Moreover, the experiment was confined to Earth lit conditions and the combined Earthshine and Sunshine intersection has not been fully simulated. In this regard, we should report that the depth perception of the seeing glasses we used to simulate the space environment was estimated by using a tape measure and it was found to be underestimated by approximately one meter. In the initial phase, one investigator measured the distance difference between seeing an object with and without wearing the seeing glasses. However, this was not tested for each participant and should be reported as a limitation. The gravitational differences between Earth and Moon could not be simulated. Additionally, even though we recruited participants from the general population, 90.7% of our participants were normal weight and therefore, we could not test the effects of BMI on body mobility and visual reaction times as previously described. The participants performed each task with a 5-minute break to ensure eye adaptation from darkness to light. However, this transition was not tested but based on previous knowledge and therefore, it may have affected the performance of the participants.

DIRECTIONS FOR FUTURE RESEARCH Human colonization of the Moon will likely include a wide range of individuals. Therefore, future research should examine the lunar lighting and surface conditions on a wider age and BMI range. Depth perception attenuation due to minimal or no atmosphere as well as a dark horizon should be included in future studies. Additionally, several other conditions on the Moon should be examined—for instance, the different Sun/Earth Moon phase angles, the terrain slope angle lighting, the minimum surface illumination, the extreme magnitude of the Sun’s glare at certain angles, and the materials on the surface of the Moon. Furthermore, the Moon’s gravitational pressure effects on the eye and its correlation to operational human body mobility as well as the rapid change adaptation of humans to extreme lighting conditions should also be addressed.

Given that our participants were recruited from the general population, we may need to explore the physiological differences between well-trained astronauts and individuals from the general population during space missions. Therefore, our findings should be considered during planning space missions for commercial reasons and/or entertainment. Finally, we suggest that future studies should examine the chronic effects of lunar lighting and depth perception conditions on astronauts. This will test the ability of individuals to improve their body mobility under moon-like illumination.

CONCLUSIONS As humankind continues to reach for the stars and eventually inhabit other celestial bodies, many challenges exist to performing their daily surface routines, construction and mining activities. Whether an individual is a highly trained astronaut or a civilian lunar tourist, Moon surface operations require a great deal more study to maximize performance under these unfamiliar conditions. Based on our findings we conclude that astronauts may decrease their body mobility under simulated Moon lighting conditions during EVAs. However, the latter could be mitigated if the future Moon habitants have an opportunity for training before they move to the Moon. We also conclude that aging may negatively affect body mobility under simulated Moon lighting conditions, while this performance may depend on the fitness level of each individual.

METHOD The study conformed to the standards set by the Declaration of Helsinki and was approved by the Ethics Board of the Human Performance in Space Department within the Space Studies Program 2014, International Space University. We obtained written consent from 17 males and 15 females [Age (mean: 36.4, standard deviation: 12.6), BMI (mean: 22.4, standard deviation: 2.8)].

STATISTICAL ANALYSIS We calculated the VO2,max of each participant based on previous prediction equations using height in cm and age as the predictive variables. Non-parametric tests were used throughout. We used Wilcoxon signed-rank tests to assess mean differences between “continuous light” performance, “strobe light” performance and “normal Earth light” performance. Kruskal-Wallis analysis of variance (ANOVA) was used to assess mean differences between men and women. We examined the associations between age, VO2,max, BMI, “continuous light” performance, “strobe light” performance and “normal Earth light” performance using Kendall’s tau-b correlation coefficient. Linear regression was used to identify whether the associations detected by the correlation analysis persist. All analyses were conducted with PASW Statistics (version 18; SPSS Inc., Chicago, IL, USA) and a p<0.05 level of significance.
CONFLICTS OF INTEREST
The authors declare no conflicts of interest.

ACKNOWLEDGEMENTS
The authors would like to thank Ms. Tricia Larson, the Chair of Human Performance in Space Department during the “Space Studies Program 2014”, for her valuable support to complete this research project. The authors would also like to thank the participants and the staff of the “Space Studies Program 2014” for their help to complete this study.

ABOUT THE AUTHORS
Mr. Petros Dinas is a Researcher in human physiology at the University of Wolverhampton, UK and an International Space University alumnus.

Mrs. Srereekha Suresh is a Scientist/Engineer SF working in Vikram Sarabhai Space Centre of Indian Space Research Organisation.

Mr. Subbananthan Thangamani works as a Deputy Manager in the Range Safety Division at Sriharikota, India. He is responsible for safety regulations and procedures for the safe conduct of activities at the launch complex and test facilities.

Mr. Alan Zide is a Senior Technologist at National Aeronautics and Space Administration (NASA) Headquarters 300 E St SW, 9076 Washington D.C.

REFERENCES

http://dx.doi.org/10.3390/6040524
http://dx.doi.org/10.1183/09031936.00150314
**Human performance under simulated lunar lighting conditions: is it possible to walk on the moon?**

Dinas et al.


