Quantifying Proprioceptive Experience in Microgravity

SHU-YU LIN, Massachusetts Institute of Technology, USA
KATYA ARQUILLA, Massachusetts Institute of Technology

In microgravity, the proprioceptive system undergoes adaptations due to the lack of constant gravitational cues. Photo-video evidence and informal accounts of microgravity exposures demonstrate a shift in the quality of movements and the self-awareness of one's body. We have designed a conceptual framework to investigate this shift and to document the effects of the microgravity environment on the proprioceptive system, which will be validated with a wearable sensor system garment user-tested by a participant on an upcoming parabolic flight.

We present the conceptual framework designed to investigate and quantify proprioceptive adaptation through the metric of fluidity, a concept drawn from ballet and dance. While fluidity is an artistic quality of movement, it can also be quantitatively measured through biomechanical properties, such as smoothness. Providing a framework for understanding proprioceptive adaptation to microgravity through an artistic lens will enable a deeper understanding of human response and the aspects of spacecraft design that will interact positively with future space travelers. Experiencing microgravity in space or during parabolic flight is a uniquely formative experience only afforded to a small fraction of Earth's population. Through presenting an aspect of what microgravity can feel like with quantitative data and written reflections, we can provide relatability and accessibility to spaceflight.

This paper covers the approach to quantifying a facet of the microgravity experience using a wearable sensor system, proposes the fluidity framework of understanding proprioceptive adaptations through an artistic lens, and explores the value of evaluating bioastronautical engineering problems through a transdisciplinary context.

CCS Concepts: • **Applied computing** → *Life and medical sciences*; *Aerospace*; • **Human-centered computing** → **Interaction design theory, concepts and paradigms**.

Additional Key Words and Phrases: wearable, sensor systems, arts

ACM Reference Format:
Shu-Yu Lin and Katya Arquilla. 2022. Quantifying Proprioceptive Experience in Microgravity. *ACM Trans. Graph.* 37, 4, Article 111 (August 2022), 5 pages. https://doi.org/XXXXXXX.XXXXXXX

1 MOTIVATION

Microgravity poses a significant challenge for human physiology and health, in particular to proprioceptive and neurovestibular systems. Heavily dependent on gravitational cues, these systems are responsible for balance, movement control, and movement awareness [7]. Spaceflight often conjures up images of crewmembers performing elegant and graceful somersaults through the spacecraft, but novice flyers in their first parabolic flights are often seen flailing, with little control over their movements [9]. Therefore, it can be hypothesized that there is a time-dependent adaptation process for re-learning controlled movements, and this process has been recorded in some individuals during parabolic flight [11]. Inappropriate control strategies may harm equipment and the crewmember; sensorimotor adaptations due to long-duration flight may also put the crew at risk in certain landing situations [11] [2].

To characterize the process of proprioceptive adaptation in short-duration exposure to microgravity, we propose the metric of fluidity. Drawing from qualitative assessments of human movement in spaceflight, dance, and underwater,

Authors' addresses: Shu-Yu Lin, shuyulin@mit.edu, Massachusetts Institute of Technology, 70 Vassar St., Cambridge, Massachusetts, 02139, USA; Katya Arquilla, Massachusetts Institute of Technology, arquilla@mit.edu.

2022. Manuscript submitted to ACM

fluidity is a familiar concept to most but challenging to quantify. This paper discusses the conceptual framework of utilizing fluidity to investigate proprioceptive adaptation and the resulting experimental design. Along with visual analysis of movement during flight and post-flight interviews, the fluidity index derived from flight data will provide a holistic understanding of the proprioceptive adaptation process.

2 RELATED WORK

Kitsou Dubois is the pioneer in bridging dance and microgravity, and she proposed that familiarity with dance can help enhance proprioceptive awareness and control over movements while in microgravity [4]. The concerns of the dance discipline heavily depend on the proprioceptive experience, including maintaining postural control and awareness of the inertias of limb segments. Exposure to proprioceptive training can aid in the adaptation to the microgravity environment, potentially alleviating motion sickness [4].

Some groups have conducted studies to quantify physiological responses to microgravity through objective measurement. Johnson *et al.*, 2018 leveraged wrist-mounted wearable sensor systems to collect heart rate, skin conductance (sweat), skin temperature, and 3-axis acceleration data during parabolic flight. Subjective measurements of nausea, anxiety, and excitement were then compared to changes in physiological response to build an understanding of objective measurement of the physiological response to microgravity [6].

Wearable sensor systems have also been leveraged for human spaceflight to quantify biomechanical and gait changes during interaction with the spacesuit. Fineman *et al.* measured biomechanical changes using inertial measurement units mounted on the legs, and Shen *et al.* proposed a full-body sensor suit to assess contact pressures and biomechanical changes during spacesuit interaction. Both studies, among others, strove to understand biomechanical adaptations to the spacesuit environment, and this approach can be leveraged to inform a broader understanding of the bulk physiological response to the microgravity environment [5][10].

Prior parabolic flight investigations by Stirling et al. showed that some participants adapt to fine-control strategies that correspond with lower joint torques and surface push-off forces [11]. Camurri *et al.* proposed a multi-layer framework that describes the tiers of movement quality in increasing order of complexity; layer 1 involves kinematics (joint trajectories), layer 2 is the biomechanical feature of joints at a small time scale (smoothness), and layer 3 is the complex quality prescribed to a longer duration of movement (rhythm, flow) [3]. Previous work by Piana *et al.* utilized this multilayer framework to create a measurable definition of fluidity, relating a complex level 3 quality to a predefined level 2 biomechanical property. To be fluid via their definition, a movement must be [8]:

(1) Smooth, via the biomechanical definition (minimum square mean of the jerk, the derivative of acceleration)
(2) Efficient propagation along kinematic chains and minimization of dissipation of energy

The conceptual framework and experiments presented herein integrate aspects of the aforementioned approaches to develop a more complete understanding of the human response to microgravity.

3 FRAMEWORK DEVELOPMENT

To investigate proprioceptive adaptations in microgravity, the adaptions are more holistically understood in the context of a broader set of physical adaptations. In Figure 1, *physical instinct* is shown as the largest circle, representing all physical and physiological adaptations from the headward fluid shift to muscle atrophy [7]. Within this broad field, *proprioceptive competence* is of special interest, since this system is one of the most affected during spaceflight [9]. We define proprioceptive competence to be:

(1) Adaptability to novel environments
(2) Capability of sustaining nominal tasks in the given environment

As reported by Stirling *et al.*, we see demonstration of proprioceptive competence in the adaptation of fine-control strategies, albeit subject to individual variation. Fluidity is proposed as the metric by which to measure proprioceptive competence, following the definition provided by Piana *et al.* To measure fluidity, a wearable sensor system garment has been developed. With an accelerometer located at each limb joint, the wearable garment records linear acceleration and rotational motion data, from which a fluidity index can be calculated.

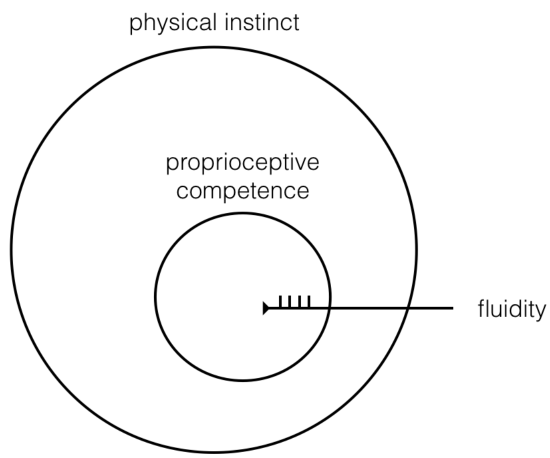

Fig. 1. Visual representation of the proposed fluidity framework. Physical instinct encompasses the changes and adaptations (such as headward fluid shift) when exposed to microgravity. Proprioceptive competence is a subcategory. Fluidity is proposed as a metric to measure proprioceptive competence.

3.1 Experimental design

Since proprioceptive competence requires a comparison before and during a microgravity experience, similar tasks must be developed for flight and ground testing to ensure consistency across experimental contexts.

The participant is given a simple translation task in flight to capture data during movement and stabilization. During each microgravity parabola, the participant is instructed to push off of the plane floor, reach the other side of the aircraft cross-section, then return to the floor. Data will be collected and separated for each parabola (a total of 16 will be available for data-gathering in the parabolic flight). The ground experiment involves the ground-equivalent of translation, wherein the participant is instructed to rise from a sitting position, traverse some distance, traverse back, and then return to the seat. The distance is determined by the maximum distance afforded in the parabolic traverse due to the cross-sectional height of the aircraft. A fluidity metric will be assigned to each parabola and compared to the results from 1. the ground-control experiment and 2. across parabolas for each participant. These two data comparisons will address the respective definitions for proprioceptive competence.

The proprioceptive experience in microgravity is not confined to joint kinematic data alone. Quantitative analysis from video data and anecdotal evidence from post-flight interviews contribute to a holistic understanding on the proprioceptive adaptation process.

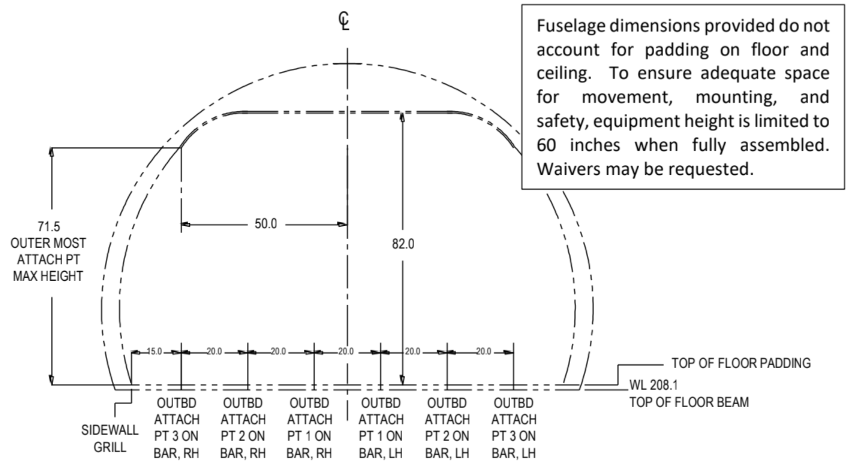

Fig. 2. Fuselage of ZeroGravity Corporation parabolic flight aircraft.

4 APPLICATIONS AND FURTHER WORK

4.1 Wearable technology for movement augmentation

Inadequate proprioceptive adaptation poses risks for equipment damage and crewmember injuries for short-duration flights [11]. In more complex mission architectures to the Moon and Mars with repeated transitions from partial gravity to microgravity environments, this risk is exacerbated [2]. This framework drove the development of a wearable sensor system to quantify fluidity, and this system can be leveraged in the future for crewmember training and to inform wearable technology for augmenting movements to prevent injuries.

4.2 Future space habitat and suit design

Our framework introduces an approach to quantifying the microgravity experience through continuous monitoring of the participant's interactions with the environment; furthering this approach, the same type of continuous measurement could be used to evaluate different space habitats in virtual and augmented reality environments. Space habitat design has traditionally been challenged by the time and material costs of developing full mock-ups to assess alternative designs. Virtual and augmented reality have been used to mitigate these issues, but they rely on discrete measurements of user experience [1]. This proposed approach could be integrated into future high-frequency commercial spaceflight missions to augment our understanding of the human response to microgravity to refine spacecraft interiors. Data about movement quality and proprioceptive adaptation are especially relevant to interior design for physical ergonomics and spacesuit design.

4.3 Integrating transdisciplinary methods into bioastronautical engineering

Given the complexity of human experience and the many changes that occur upon entering microgravity environments, bioastronautical engineering has historically benefited from the influence of other research disciplines—textile designers have been key in the development of spacesuit soft goods, microbiologists lead research efforts to understand the spaceflight environment, psychologists investigate the impacts of the isolated, confined, extreme environment that is space, and more. Despite this interdisciplinary culture in bioastronautics, the field has not yet embraced methods drawn from the performing arts. The framework presented here provides an approach to leveraging what is known about human movement in dance to develop a deeper understanding of the human experience in microgravity.

4.4 Expanded access to the microgravity experience

The ability to quantify the microgravity experience has the potential to make the sharing of this experience with the public more impactful. Given the highly selective access to the microgravity experience, it is essential to provide those with the privilege to have this experience the tools to effectively share their formative experience with those that remain on Earth. These tools will contribute to an increase in relatability and accessibility to spaceflight for the general public—a key aspect of ensuring the future of the human exploration of space.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. 1745302 and the MIT Jack and Vickie Kerrebrock Fellowship.

Thank you to Prof. Jeffrey Hoffman, Dr. Ariel Ekblaw, and all the experts from the 16.88 course (Prototyping our Sci-Fi Space Future: Designing & Deploying Projects for Zero Gravity Flights) for their feedback.

Thank you to the Space Exploration Initiative for their support in making the parabolic flight opportunity possible.

Thank you to the MIT Graduate Student Council and Massachusetts Space Grant for their support.

Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

[1] Neil T. Banerjee, Alex J. Baughman, Shu-Yu Lin, Zoë A. Witte, David M. Klaus, and Allison P. Anderson. 2021. Development of alternative reality environments for spacecraft habitat design evaluation. *Virtual Reality* 25, 2 (June 2021), 399–408. https://doi.org/10.1007/s10055-020-00462-6

[2] J. J. Bloomberg, M. F. Reschke, Clement G. R., Mulavara A. P., and Taylor L. C. 2016. Risk of Impaired Control of Spacecraft/Associated Systems and Decreased Mobility due to Vestibular/Sensorimotor Alterations Associated with Space Flight. (2016).

[3] Antonio Camurri, Barbara Mazzarino, Matteo Ricchetti, Renee Timmers, and Gualtiero Volpe. 2004. Multi-modal analysis of expressive gesture in music and dance performances. *Gesture-based communication in human-computer interaction* (2004), 20–39.

[4] Kitsou Dubois. 1994. Dance and Weightlessness: Dancers' Training and Adaptation Problems in Microgravity. 27 (1994), 57–64. Issue 1. https://muse.jhu.edu/article/606885/summary

[5] Richard A. Fineman, Timothy M. McGrath, Damian G. Kelty-Stephen, Andrew F. J. Abercromby, and Leia A. Stirling. 2018. Objective Metrics Quantifying Fit and Performance in Spacesuit Assemblies. *Aerospace Medicine and Human Performance* 89, 11 (Nov. 2018), 985–995. https://doi.org/10.3357/AMHP.5123.2018

[6] Kristina T. Johnson, Sara Taylor, Szymon Fedor, Natasha Jaques, Weixuan Chen, and Rosalind W. Picard. 2018. Vomit Comet Physiology: Autonomic Changes in Novice Flyers. In *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. 1172–1176. https://doi.org/10.1109/EMBC.2018.8512414 ISSN: 1558-4615.

[7] Peter Norsk. 2018. *Physiological Effects of Spaceflight – Weightlessness: An Overview.* Springer International Publishing, Cham, 1–9. https://doi.org/10.1007/978-3-319-10152-1_126-1

[8] Stefano Piana, Paolo Alborno, Radoslaw Niewiadomski, Maurizio Mancini, Gualtiero Volpe, and Antonio Camurri. 2016. Movement Fluidity Analysis Based on Performance and Perception. http://dance.dibris.unige.it/

[9] Rachel D. Seidler and Ajitkumar P. Mulavara. 2020. *Sensorimotor Adaptation, Including SMS.* Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-10152-1_22-2

[10] Young-Young Shen, Abhishektha Boppana, Katya Arquilla, and Allison P. Anderson. 2018. Wearable sensor suit system for quantifying human-spacesuit interactions. In *2018 IEEE Aerospace Conference*. 1–13. https://doi.org/10.1109/AERO.2018.8396681

[11] Leia Stirling, Karen Willcox, Philip Ferguson, and Dava Newman. 2009. Kinetics and kinematics for translational motions in microgravity during parabolic flight. *Aviation Space and Environmental Medicine* 80 (6 2009), 522–531. Issue 6. https://doi.org/10.3357/ASEM.2356.2009