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Next-Generation Fluids-Related Biology Research Utilizing the Zero Gravity Research Facility at NASA Glenn Research Center

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Abstract

To gain insight into how cells sense gravity, NASA has developed a platform to investigate the transient response of biological cells to a sudden exposure to microgravity. The Zero Gravity Research Facility offers unique capabilities and opportunity to investigate this phenomenon. A review of current literature indicates that it remains unclear how biological cells sense and respond to gravitational forces, although it is believed that a combination of biostructural and fluid transport mechanisms are at play. This Technical Memorandum outlines a pathway to address this fundamental biological challenge. A series of low-cost, systematic drop tower experiments were conducted to observe the biomechanical behavior of cell membranes (such as vestibular hair, endothelial, and bone cells) that are known to exhibit sensitivity to gravity. These experiments demonstrated a useful, low-cost experiment concept that can potentially be employed by researchers interested in observing, identifying, and characterizing changes in biological cell morphology.

Introduction

NASA is seeking to more fully understand how cells sense gravity and microgravity and what triggers their adaptive responses in different gravity conditions. Biological organisms have evolved and are programmed to survive in an environment where a gravitational force of 1g is ubiquitous. Understanding fundamental biological cellular phenomena related to gravity, particularly the sensing of gravity and the response to varying gravity levels, is essential for future space exploration and colonization of space by humans. Leading scientists recognize that a large gap exists in the understanding of physiological and molecular adaptations that occur as biology enters the spaceflight realm (Refs. 1 and 2). A fundamental understanding of how cells respond and react in a microgravity environment will provide new and necessary insights into how organisms respond and adapt to the space environment (Ref. 3). This fundamental understanding carries translational value across the spectrum of organisms involved in space exploration, including humans.

Investigating biological cellular phenomena using a drop tower represents a new research tool in the understanding of biological systems. This research methodology has the potential to advance scientific understanding of biological cellular phenomena by offering facile and repeated access to high-quality microgravity. The outcomes could provide significant benefits toward NASA's current and future plans for physical science and biomedical technologies in space (Ref. 4). The goal is to open a new, low-cost research capability for biologists by augmenting long-duration International Space Station (ISS) science capabilities. This capability will serve as a validation and verification methodology for future microgravity fluids projects investigating biological organisms. It will provide valuable input toward development of a physics-based model to capture biological cell phenomena. To this end, initial setup, calibration testing, and feasibility testing were conducted, and an initial real-world experiment was performed using the new technique. A description of the experimental capabilities is provided below.

Zero Gravity Research Facility

The Zero Gravity Research Facility at the NASA Glenn Research Center (Figure 1) is currently used by NASA-funded researchers from around the world to study the effects of microgravity on physical phenomena such as combustion and fluid physics, to develop and demonstrate new technology for future space missions, and to develop and test experiment hardware designed for flight aboard the ISS.

The Zero Gravity Research Facility provides researchers with a near-weightless or microgravity environment for 5.18 s as the experiment hardware is allowed to free fall a distance of 132 m (433 ft). The free fall is conducted inside a 143-m (470-ft) long steel vacuum chamber. The chamber is 6.1 m (20 ft) in diameter and resides inside an 8.1-m (28-ft) diameter concrete-lined shaft, which extends 155 m (510 ft) below ground level. A five-stage vacuum pumping process is used to reduce the pressure in the chamber to 0.1 torr (760 torr = standard atmospheric pressure). Evacuating the chamber to this low pressure reduces the acceleration, due to aerodynamic drag on the freely falling experiment vehicle, to less than 0.00001g. To protect experiment hardware from shock loads experienced during deceleration, an experiment drop vehicle is used as a load-bearing structure. The typical drop vehicle is approximately 1 m (39 in.) in diameter and 3.7 m (12 ft) in length, with a gross weight of up to 1,100 kg (2,400 lb).

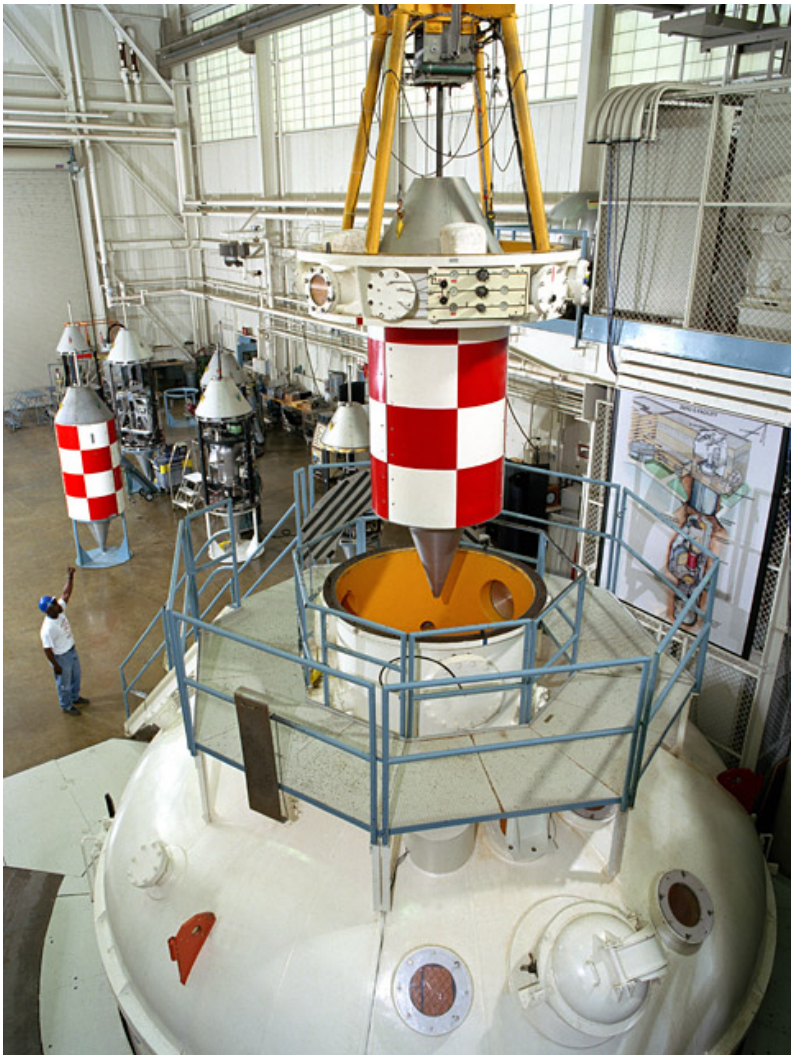

Figure 1.—Zero Gravity Research Facility at NASA Glenn Research Center.

Experimental Approach

The initial hardware checkout and calibration testing was performed in the 2.2 Second Drop Tower at Glenn. These tests were conducted to verify the ability of the imaging hardware to capture high-definition digital images while surviving the high-g deceleration (~25g) that occurs at the end of the 80-ft free fall. The initial tests utilized a GigE Vision® (AIA) camera with 640´ 480 resolution and capable of up to 300 frames per second (fps). The camera was mated with a large-field telecentric gauging lens (Invaritar® 59 LGH 416 (Melles Griot), 121 by 84 mm diam.) and imaged on the standard USAF 1951 resolution test chart. The hardware setup is shown in Figure 2. Follow-on tests in the 2.2 Second Drop Tower were conducted and imaged readily available fluids such as gel, olive oil, and alcohol placed in a 10-mm path length quartz cuvette (Figure 3). After digital images were successfully captured in the 2.2 Second Drop Tower, similar tests were repeated in the Zero Gravity Research Facility to verify the capability of the imaging hardware to survive the higher deceleration rate of 65g. These preliminary experiments demonstrated an ability to detect and measure phenomena at a scale similar to morphological cellular phenomena, which will be applied to Zero Gravity Research Facility experiments (Refs. 5 and 6).

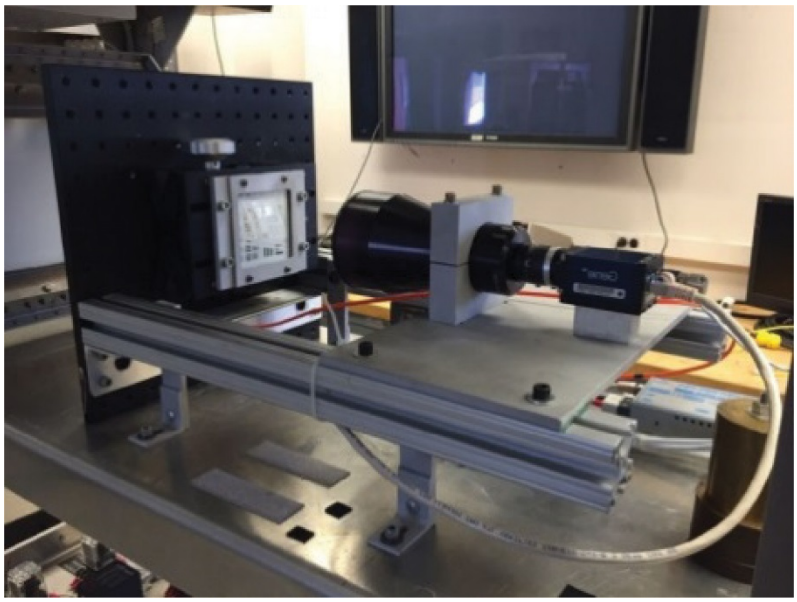

Figure 2.—Initial hardware setup.

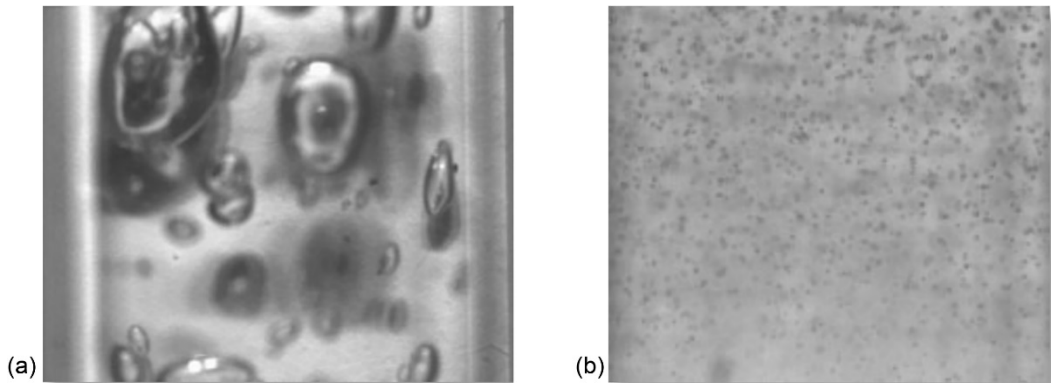

Figure 3.—Images captured utilizing initial hardware setup. (a) Olive oil. (b) Water.

As an initial experiment, a series of plant root signal transduction experiments investigating *Arabidopsis* plant species (Figure 4, Figure 5, and Figure 6) was conducted under the direction of Robert Ferl (Ref. 2). Ferl, an active ISS spaceflight principal investigator, suggests that the early first few seconds of transitional adaptation from gravity to microgravity is an unknown caused largely by the lack of access to facilities that allow the study of that transition.

For these experiments, the test setup was improved by replacing the initial GigE camera with a DALSA Genie Nano M2590 Mono (Teledyne DALSA Inc., part number G3-GM10-m2590), which provided a resolution of 2592´ 2048 pixels at up to 51 fps. The camera was mated with the same large-field telecentric gauging lens that had been tested previously (InvaritarÔ 59 LGH 416 (Melles Griot), 121 mm in length by 84 mm in diameter). *Arabidopsis* fluorescence was excited by four circular, 34-mm-diameter light-emitting diode (LED) assemblies from LEDtronicsÒ (LEDtronics, Inc.). These LEDs produced blue light centered about 470 nm. The LED assemblies were enclosed and the emitted light was filtered by Edmund OpticsÒ shortpass filters (Edmund Optics Inc., stock number 84-706), which passed light at wavelengths from 300 to 490 nm. Light entering the camera lens was further filtered by an 82-mm diameter, lens-mounted bandpass filter (model 515BP10) from Omega Optical, Inc. This filter allowed light centered around 515 nm into the video imaging system.

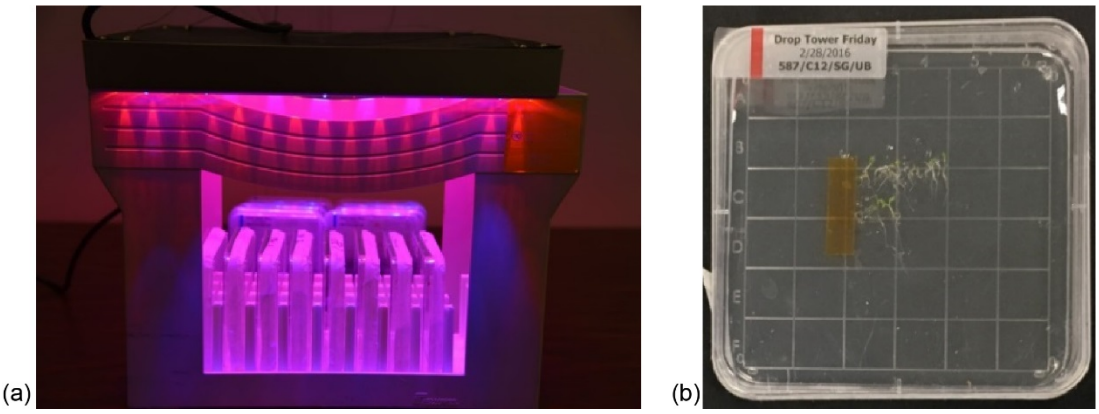

Figure 4.—*Arabidopsis* plant experiment. (a) *Arabidopsis* plates under LED grow lights. (b) *Arabidopsis* plate just before experiment drop.

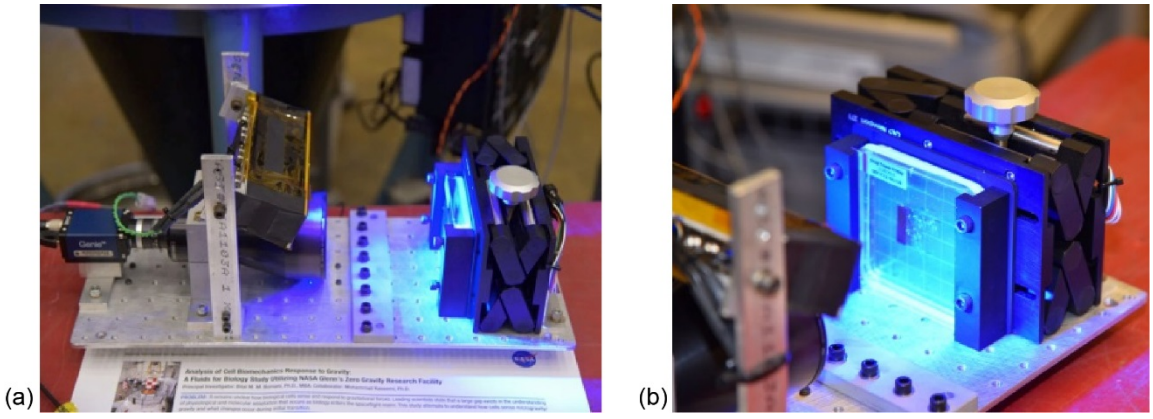

Figure 5.—*Arabidopsis* plant experiment during pre-drop check and optimization. (a) Hardware setup. (b) *Arabidopsis* plate in fluorescent imager with excitation LEDs illuminated.

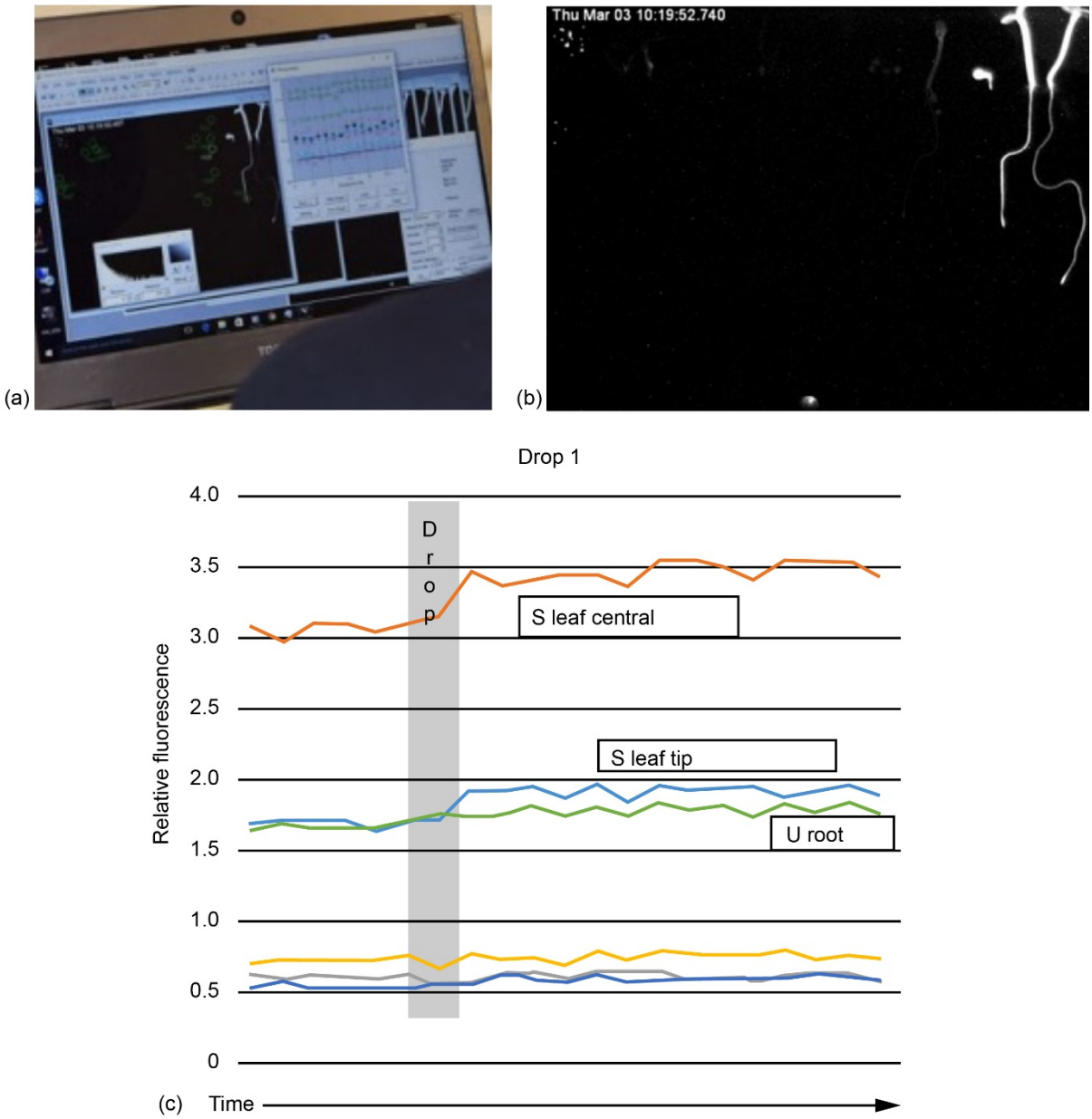

Figure 6.—Analysis of *Arabidopsis* plant experiment. (a) Analysis software. (b) Closeup image of seedlings, with constitutively bright seedlings to the right of the frame. (c) Quantitative analysis showing changes in fluorescence intensity in various plant parts while control fluorescent beads do not change.

As shown in Figure 6(a) and (b), individual frames were rendered from the Audio Video Interleave (AVI) video files recorded by the test hardware before and during the drop. Quantitative analyses were used to follow changes in fluorescence intensity through the duration of the drop, as shown in Figure 6(c). Fluorescent beads, signified by the yellow, gray, and blue lines in Figure 6(c), were used as internal standards along with constitutively expressing biosensor plants (green line). These fluorescence intensities did not change through the course of the drop. The orange line and the light blue line both show change in fluorescence in seedling leaf parts that quickly change in intensity during the drop. These data suggest that fluorescent tools commonly used in the study of biological signaling can be used in the drop tower to assess the early biological signals accompanying changes in gravity. These preliminary findings show great promise for the proposed experiment methodology for fluids for biology experiments (Ref. 7).

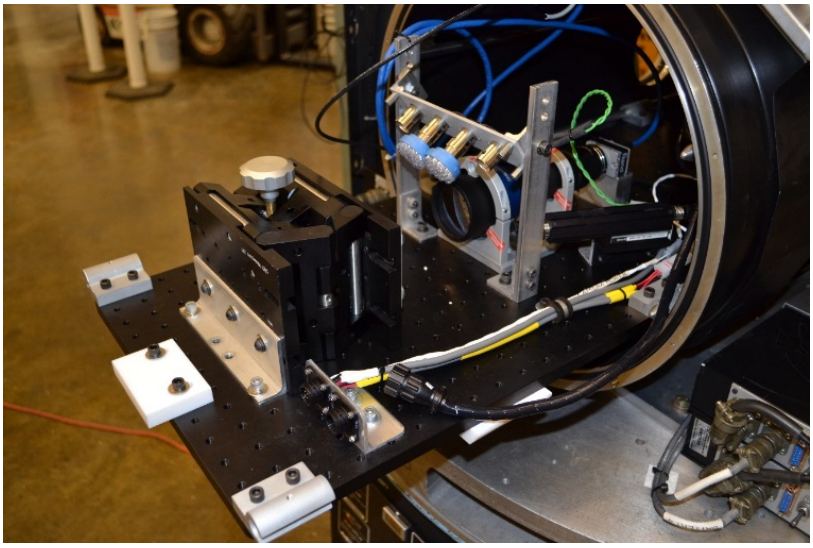

Figure 7.—G drop vehicle chamber with optics plate containing hardware for fluorescent imaging of biological samples in NASA Glenn Zero Gravity Research Facility.

State-of-the-Art Research Capabilities

To continue utilizing an improved drop testing capability, a new drop vehicle for use in the Zero Gravity Research Facility has been assembled specifically to support fluids for biology experiments. The new drop vehicle includes a larger test chamber that is able to accommodate larger experiments and diagnostics equipment than could be accommodated in the Phase 1 experiments. The new, next-generation fluids for biology chamber is 81 cm (32 in.) long by 40 cm (15.75 in.) in diameter and has an internal volume of approximately 0.105 m^3 (6400 in^3). The chamber has three orthogonal, 11.4-cm (4.5-in.) diameter windows located at the center of the chamber for imaging the experiment inside. The chamber is also equipped with the appropriate feedthroughs such that imaging equipment can be mounted inside the chamber when the chamber test environment allows. The chamber is mounted horizontally on the drop vehicle. An 81- by 33-cm (32- by 13-in.) optics plate with 2.5-cm (1-in.) on-center, 1/4-20 UNC tapped holes is available for installation of experiment hardware inside the chamber. The optics plate attaches to internal rails that enable the experiment to slide in and out of the chamber for easy access (Figure 7).

A number of video imaging formats can be supported and recorded by the video data acquisition systems available on the drop vehicle. Current imaging capabilities include high-resolution video (2592˝ 2048 at 51 fps—DALSA Genie Nano M2590 Mono (Teledyne DALSA Inc.); 5120˝ 5120 at 72 fps—ISVI IC-M25S-CXP-FM (ISVI Corp.); and 2560˝ 1440 at 30 fps—SJCAM SJ5000 WiFi (SJCAM)). A number of telecentric C-mount and Nikon bayonet-type F-mount lenses (Nikon Inc.) are available for these cameras. The drop vehicle is also equipped with a data acquisition unit capable of recording 32 analog channels at a maximum sampling rate of 50 kHz (aggregate) to a Class 10 (or better) flash memory card. Instrumentation input voltage ranges are ±100 mV filtered at 100 Hz, ±5 V filtered at 500 and 1000 Hz, and ±10 V unfiltered. The capabilities of the Zero Gravity Research Facility and 2.2 Second Drop Tower are summarized in Table I and Table II, respectively. In addition to the fluorescent imaging capability, thermal imaging capabilities are planned for incorporation into the next-generation fluids for biology chamber. Fluorescent gene expressions with some hints of measurable

TABLE I.—ZERO GRAVITY RESEARCH FACILITY CAPABILITIES

Microgravity duration, s	5.18
Maximum number of experiments per day	2
Acceleration environment, g	~10^{-5}
Deceleration load, g	35 average with peaks to 65
Biofluids chamber size, m^3 (in^3)	0.105 (6400)
	81 cm (32 in.) long by 40 cm (15.75 in.) in diameter
Biofluids specimen size, mm (in.)	12.7 by 12.7 to 152.4 by 152.4 (0.5 by 0.5 to 6 by 6)
Experiment power	24-Vdc, 5-Ah packs
Available camera imaging resolution, pixels	2560´ 1440 at 30 frames per second (fps)
	2592´ 2048 at 51 fps
	5120´ 5120 at 72 fps
	640´ 480 at 300 fps
	2560´ 1920 at 800 fps
	1920´ 1080 at 2,000 fps
Data acquisition	32 analog channels at 50 kHz (aggregate)
Lens type	Nikon or C-mount compatible

TABLE II.—2.2 SECOND DROP TOWER CAPABILITIES

Microgravity duration, s	2.2
Maximum number of experiments per day	12
Acceleration environment, g	~10^{-3}
Deceleration load, g	15 average with peaks to 30
Maximum experiment volume, cm (in.)	96 by 84 by 40 (38 by 33 by 16)
Maximum experiment weight, kg (lb)	159 (350)
Biofluids specimen size, mm (in.)	12.7 by 12.7 to 152.4 by 152.4 (0.5 by 0.5 to 6 by 6)
Experiment power	24-Vdc, 5-Ah battery packs
Available camera imaging resolution, pixels	2560´ 1440 at 30 frames per second (fps)
	2592´ 2048 at 51 fps
	5120´ 5120 at 72 fps
	640´ 480 at 300 fps
Data acquisition	32 analog channels at 50 kHz (aggregate)
Lens type	Nikon or C-mount compatible

reactions have been observed in Phase 1 of the feasibility experiments. A considerable amount of data from parabolic flights indicate that thermal change in plant leaves occurs within 5 s of the g-change during the parabola (1.8g to 0g), but these data suffer from inconsistent g-level results typical of parabolic aircraft flight. The drop tower facility transition from 1g to 0g is clean and consistent, which will enable researchers to validate data and modeling for which there is a known biological effect. Thermal imaging provides a unique window into biological phenomena that are known to occur, but at a scale and quality no one has ever seen before.

The Zero Gravity Research Facility enables the possibility of a cross-disciplinary research collaboration between biological and physical scientists to compare and validate numerical models. Currently, the computational approaches applied in the area of cellular membrane analysis in microgravity can be grossly classified into continuum and discrete methods. These methods are inherently suited to predict stress and strain changes within the continuum but are at a disadvantage in isolating the behavior and contributions of individual cellular components such as cytoskeletons. The Zero Gravity Research Facility will utilize existing computational cell models following a fluid–structural interaction approach that will combine the advantages of the continuum and discrete models. The physiological

fidelity of the model will ultimately be validated as part of a future validation and verification process using the results of the drop tower experiments (Refs. 8, 9, and 10).

Concluding Remarks

Scientists seek to investigate the transient response of biological cells to a sudden exposure to microgravity. The Zero Gravity Research Facility offers unique capabilities and opportunity to investigate this phenomena. This research phenomena was addressed by developing an experimental protocol for conducting a series of low-cost systematic drop tower experiments to observe the biomechanical behavior of cell membranes (such as vestibular hair, endothelial, and bone cells) that are known to exhibit sensitivity to gravity. This experimental concept can potentially be employed by space biology researchers around the world interested in observing, identifying, and characterizing changes in biological cell morphology. Ultimately, the intention is to formulate a uniform methodology for conducting experiments that can be incorporated into existing International Space Station (ISS) experiment protocol and used for future space biology validations.

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