A Perturbation Platform System for Balance Testing and Rehabilitation Interventions

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Methodology

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Abstract

Background

Falling is a leading cause of injury and death in the United States. Researchers and clinicians strive to identify and rehabilitate those at risk of falling in order to mitigate the impact of fall events and prevent future falls. Recently, perturbation-based balance testing and interventions have received increased attention, partly because reactive postural control responses triggered by perturbations are important for balance recovery during actual falls. However, current systems are limited by the need for multiple individuals to operate the device, downtime between trials to reset the perturbation and/or single mode functionality. To this end, we have developed a Perturbation Platform System that can induce perturbations in both vertical and angled directions.

Results

The system consists of two box platforms that can individually perform straight (25.4 mm, 50.8 mm and 76.2 mm) and angled (5°, 10°, and 15°) height changes while an individual is standing or walking overground. In addition, the system can automatically reset to the original position following perturbation. The platform achieves peak downward accelerations of 5.41 m/s2 during drop events that simulate sudden changes in foot-contact surfaces.

Conclusions

The novel system can be used in a laboratory setting to better understand balance response and control mechanisms. In addition, this portable system can be used in a clinical or home setting to provide perturbation-based balance exercises that aim to improve balance and mobility.

Background

Falling is one of the leading causes of both fatal and non-fatal injuries in the United States. In 2017, falling accounted for over 70,000 deaths and 17 million nonfatal trips to the emergency room [1, 2]. Among older adults, falling is the leading cause of death due to unintentional injury with a 31% increase in incidents from 2007–2016 [3]. Research has shown that 30–60% of older adults experience a fall each year [4]. Individuals with stroke also face balance control deficits that lead to 73% of stroke survivors falling within the first six months after discharge and 50% within the first year [5, 6]. Similarly, the amputee community experience major health risks as a result of falling with more than half of lower limb amputees reporting falls over the previous year and 75% of those reporting multiple falls [7, 8]. In addition to the potential for significant injuries, falling can have negative consequences related to psychological and social aspects of daily living with individuals who experience a fall often limiting their physical activity and social interactions due to fear of falling [9].

With falling being a critical clinical problem, researchers and clinicians often seek to develop assessment and intervention methods to both identify those at risk of falling and help reduce the risk of future falls. Studies have shown promising results in identifying mechanisms underlying balance deficits in several populations utilizing primarily horizontal perturbations. For example, a motor-driven cable system [10] was used to apply a lateral pull to the pelvis to study reactive stepping in older adults [11] and individuals post-stroke [12]. Others have used unexpected forward and backward platform translations to study postural reflexes in individuals post-stroke [13].

Treadmill acceleration/deceleration and sideways translations have also been used to study balance control in young and older adults [14]. These early systems focused primarily on horizontal perturbations, however, falls often involve vertical displacements. As a result, more recent work has utilized vertical perturbations to assess startle reactions and balance control [15]. This system had subjects standing on a platform over an in-ground force plate. With computer control, electromagnets would release the standing surface and induce a drop perturbation. However, a limitation of the system was that resetting required the subject to step off the platform while it was manually reset. Other studies have used a pneumatically actuated platform to facilitate weight transfer during step initiation in individuals with Parkinson’s disease [16, 17]. However, this system could only perform unilateral perturbations and was limited to 15 mm of vertical displacement.

In addition to platform translations, studies have used angled surfaces to simulate uneven terrain. A static device that could vary the surface angle up to 15° in inversion or eversion was designed to assess balance recovery mechanisms on uneven terrain in individuals with lower-limb amputations [18]. This device was designed to sit atop a standard in-ground force plate with the individual walking unilaterally over the uneven surface on an elevated walkway. The angle of the surface was modulated manually, with two individuals being needed to manipulate the top plate into the orientations of interest.

Current devices are often limited by the need for multiple individuals to operate the device, downtime between trials to reset the perturbation, singular functionality, and/or the capability to only test unilateral or bilateral perturbations. To overcome these limitations, the purpose of this paper was to present a novel Perturbation Platform System that was designed to perform multiple perturbation types and automatically reset itself between trials without the test subject leaving the platform.

Methods

Design

The design of the Perturbation Platform System was guided primarily by the goal to operate the device remotely by a single individual and reset to the start position on command while supporting the participant’s body weight. The system was designed to provide a sudden vertical displacement of the standing support surface up to 76.2 mm and provide either unilateral or bilateral perturbations. This distance was selected because it is sufficient to trigger a rapid postural reaction for balance recovery and the impact force is reasonable (approximately 1 bodyweight) for safe, repeated exposures [15]. The platform can also tilt up to 15° in both directions providing the ability to perform ankle inversion/eversion or plantarflexion/dorsiflexion perturbations depending on orientation. These angle magnitudes have been established to provide a maximum perturbation without risk of injury [18]. In addition, the platform was designed to be triggered on foot contact from the user, allowing the direction and distance of the drop to be concealed to simulate unexpected perturbations. Lastly, the system is relatively portable such that it can be moved by a single individual for setup in a gait laboratory or used in a clinical setting. To this end, the main components of the system were constructed from ABS plastic with 2 platform units each weighing 25 kgs, measuring 406 mm wide x 508 mm long x 236 mm tall and include handles for ease of transport (Fig. 1). Final implementation in the laboratory setting includes in-ground force plates directly beneath each platform and an elevated stage surrounding the system to facilitate overground walking trials as well as helping to alleviate potential anxiety due to the sensation of height when standing on the platforms. The system is described in detail below.

The Perturbation Platform System consists of three main components: 1) two movable standing surfaces, 2) a high-pressure air source, and 3) a remote control interface (Fig. 1). The operation of each platform utilizes four, double acting, pneumatic pistons (Space Saver Low Profile, SS-150, Mead Fluid Dynamics, Chicago, IL, USA) (Fig. 2A). Each piston features 76.2 mm of travel with the capability to lift 80 kg at a working pressure of 6.9 Bar. With four pistons per platform, each platform can lift a 320 kg person or 640 kg when two systems (i.e., bilateral perturbations) are used together. The system is controlled via a 5/3 directional air valve (IMI Norgren, K81EA00KV0KV02W1, Littleton, CO, USA) (Fig. 2B). The valve is controlled with two 12-volt solenoids that can be activated or deactivated to raise or lower the pistons. The use of the 5/3 valve allows for directional control of the pistons along with a third mode where airflow is closed, which is activated when no electrical signal is applied. This provides a safety feature in the event of power loss that will lock the pistons in place without dropping the subject unexpectedly. A single, high-pressure air source is provided from an external compressor (Fig. 2C). Currently, the compressor source is in a separate room with the air line routed through the floor to provide quiet and discreet operation of the platforms. Air is supplied and exhausted from the pistons evenly via two distribution blocks (Fig. 2D). An exhaust muffler helps to quiet exiting air to prevent startling participants or alerting them to the timing of upcoming perturbations (Fig. 2E). Lastly, each piston is fitted with a one-way variable flow control valve at the inlet/outlet to allow for speed control of the piston drop and return.

Movement of the upper platform is controlled via four, 12-volt, sealed linear solenoids (Magnet Shultz of America, S-07791, Westmont, IL, USA) (Fig. 3A). The linear movement of the top plate is then guided up and down on four V-Groove track roller and rail elements (Fig. 3B and 3C, respectively). The linear solenoids are threaded into brass inserts (Fig. 3D) that are pressed into the moving top plate and contain a hardened steel pin. When the 12-volt signal is applied the pin is retracted into the solenoid. When the signal is removed an internal spring pushes the pin outward to mate with a corresponding brass insert (Fig. 3E) on the two end plates of the platform box. The solenoids and pins allow for the selection of different drop types (straight vs angle drop). When all pins are retracted the plate is guided by the track rollers and drops straight down. When a single pair of pins is engaged on opposite ends of the platform the top plate rotates around the axis created by the pins to enable angled orientations in both directions (i.e., inversion/eversion or plantarflexion/dorsiflexion). During angled operation, the track rollers lose contact and the motion of the top plate is guided solely by the pins. As a safety precaution, in the event of a loss of power to the solenoids, all pins are engaged resulting in the top plate being locked in the up position. To enable different levels of straight and angle drops, adjustable stops are used to provide an end position for the top plate after a drop (Fig. 2F). Six different positions are provided via predrilled holes in the end plates of the platforms. The outermost holes facilitate 25.4 mm, 50.8 mm and 76.2 mm straight drop heights while the inner set of holes allows for 5°, 10° and 15° drop angles. Lastly, to enable the top plate to drop on contact with the user, four spring pins are located just under the top plate at the corners, two in each end plate (Fig. 4). The edges of the top plate are lined with a strip of hardened steel such that the impact with the pin does not deform the plastic material. The engagement of the spring pins can be varied by moving the tips in or out in their threaded mounts in the end plates that allow for adjustments of the force magnitude required to cause them to fall.

The controller for the system utilizes a Teensy 3.2 microcontroller (PRJC Sherwood, OR, USA) (Fig. 5). The controller is hard wired to the two platforms with connectors at each end to allow for assembly and disassembly. The 4-meter lead allows for remote operation of the system by a single person from a central location in the laboratory. The controller consists of four inputs. The two on either side allow users to set the drop mode of each platform individually and includes an LED indicator to indicate the current mode of operation (straight drop, inversion/plantarflexion drop, eversion/dorsiflexion drop or all lock). The two vertical buttons in the center initiate the drop or return for both platforms simultaneously for simple activation of each test condition. Varying modes of operation can be accomplished with the two platforms combined (Fig. 6), which allows a wide range of unilateral or bilateral testing scenarios.

Performance Testing

Testing was performed to verify the function and capability of the Perturbation Platform system. A single subject (male, 1.66 meters, 73 kgs, 36 years old) provided informed consent to the testing as approved by the University of Texas Internal Review Board. While standing with one foot on each platform, the system was run through the nine configurations available (Fig. 6) and returned to the original position with the subject remaining on the platform.

In order to characterize the motion of the system, a Vicon motion capture system (Vicon, Centennial, CO, USA) was used to track the motion of a marker attached on the top plate of the platform to quantify the accelerations experienced over repeated drops. With the individual standing with one foot on each platform, five, unilateral, straight drops were performed at each drop height (Min: 25.4 mm, Mid: 50.8 mm, and Max: 76.2 mm) for a total of 15 drops. To characterize the motion of the platform the instantaneous velocity and acceleration were calculated by taking the first and second derivatives of the measured marker position over time. The derivative signals were then smoothed using a 6 Hz, lowpass, Butterworth filter and the peak downward acceleration was determined. Results from the three drop heights were then compared using a one-way ANOVA and multiple comparison test to determine overall and pairwise differences ($p < 0.05$) between the drop heights, respectively. All statistical testing performed in Matlab (MathWorks, Natick, MA, USA).

Results

Results from testing of the various configurations showed that in each of the nine scenarios the platforms were able to achieve the intended final orientation and then return to the initial starting position. The motion capture data verified the intended drop heights to be 26.9 ± 1.1, 51.1 ± 1.4 and 73.8 ± 1.6 mm for the Min, Mid and Max levels, respectively (Table 1). Instantaneous position, velocity and acceleration results are shown in Fig. 7, with similar peak downward acceleration values of -5.41 ± 0.60, -5.11 ± 0.29 and − 4.78 ± 0.20 m/s^2 found for the Min, Mid and Max drops respectively ($p \geq 0.069$).

Table 1
Results from Perturbation Platform System testing. Values are mean ± SD, significant p-values < 0.05 shown in bold.

	Drop Type			**p-value**		
	Min	Mid	Max	Min v Mid	Min v Max	Mid v Max
Drop Dist. (mm)	26.9 ± 1.1	51.1 ± 1.4	73.8 ± 1.6	< 0.001	< 0.001	< 0.001
Drop Time (s)	0.105 ± 0.016	0.170 ± 0.005	0.248 ± 0.019	< 0.001	< 0.001	< 0.001
Peak Accel (m/s^2)	-5.41 ± 0.60	-5.11 ± 0.29	-4.78 ± 0.20	0.490	0.069	0.417

Discussion

In this work, we have designed a novel Perturbation Platform System to perform multiple perturbations (standing vs walking, straight vs angled, unilateral vs bilateral) and automatically reset for the next perturbation while supporting the participant's body weight. Results from testing the straight drop of the system indicate that the platform does not reach full free fall levels of acceleration (-9.8 m/s^2). However, the acceleration values observed in the present study were similar to previous devices that successfully triggered rapid body reactions to balance perturbations. The device in Rogers et al. (2011) displaced 15 mm in 0.1 seconds, which is slower than our device that achieves 26.9 mm of displacement in 0.105 seconds. The Sanders et al. (2019) device achieves an acceleration of 4.9 m/s^2, which is also less than our peak value of 5.41 m/s^2. This indicates that our device will be able to produce comparable or improved perturbation responses as previous studies.

The inability of the platform to reach full free fall acceleration may be due to friction from the guide rollers applying an upward force to the falling plate. It can also be seen in the instantaneous acceleration results that the Max and Mid acceleration curves have a plateau of zero acceleration (constant velocity) around mid-fall while the Min curve has a smooth transition from negative to positive (Fig. 7). This may be due to the return profile of the pneumatic pistons. While viewing high-speed video, we noticed that the pistons initially move quickly from under the platform, but near mid-stroke, they slow momentarily and contact the platform before fully retracting. However, the platform motion is uninterrupted during the fall, as seen in the position plot (Fig. 7), and the perception of falling (peak acceleration) is consistent across fall heights and sufficient to illicit a perturbation response. In the future, pistons with faster retraction speeds could easily be retrofit if this behavior is found to inhibit testing.

The Perturbation Platform System is designed for both laboratory research settings and clinical training. Similar perturbation testing has been used to understand the physical and neurological implications of advanced age, stroke, lower limb amputation and Parkinson's disease influence the response to sudden, unexpected perturbations [15, 16, 18]. This device could also be used in a clinical rehabilitation setting to give individuals safe practice when encountering an unexpected perturbation. Such practice can train their neuromuscular systems to help reduce or prevent future falling [4, 16, 19]. We plan future testing with the device to identify neuromuscular and biomechanical abnormalities during balance perturbations in older adults and will assess adaptive changes in balance control following bouts of perturbation exercises.

One limitation of the current system is the hard-wired controller. However, the Teensy microcontroller is capable of Bluetooth wireless communication. In the future, versatility can be added to make the system control wireless. In addition, the control could be integrated into an existing gait lab computer system to allow the control of the platforms in unison with other lab components such as the motion capture and/or force plates. This would allow for more advanced testing conditions that could synchronize various system operations automatically to be timed with specific kinetic or kinematic events.

Conclusions

This work outlined the design and testing of a novel Perturbation Platform System that allows for unilateral or bilateral ground perturbations of individuals standing or walking in a laboratory or clinical environment. The system allows for both straight and angle drop functions under contact from an individual and can automatically reset to the original position even under the load of the participant's body weight. This system will allow for the advanced testing and rehabilitation of balance and recovery for individuals in both research and clinical settings.

Declarations

Ethics Approval and Consent to Participate

The subject in this study provided informed consent to all activities. This study was approved by the University of Texas at Austin's Institutional Review Board.

Consent for publication

Not applicable

Availability of data and materials

The dataset used and/or analyzed as a part of this study is available upon request from the corresponding author.

Competing interests

The authors declare that they have no competing interests.

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Author Contributions

CP and RN participated in the design and fabrication of the Perturbation Platform System. SS and HH collected experimental data. All authors contributed to the analysis of data and writing of the manuscript.

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Not Applicable

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Figures

Figure 1

Main components of the Perturbation Platform system: Two platform units (Right), High pressure air source (Left), and Tethered, hand-held, remote control unit (Center-bottom).

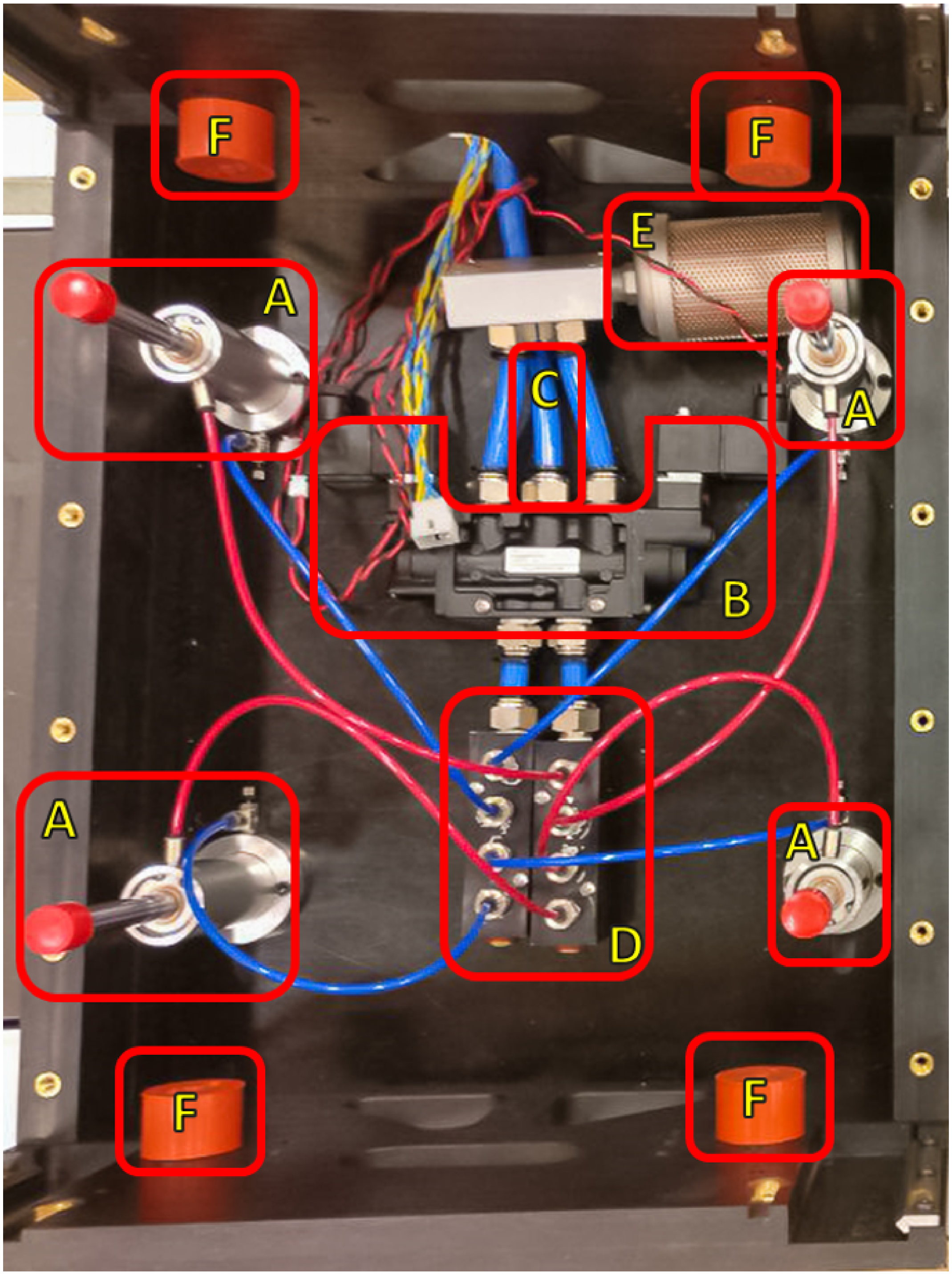

Figure 2

Internal view of a single platform. A) Four pneumatic pistons, B) 5/3 control valve, C) distribution blocks, D) high-pressure air feed, E) exhaust muffler, and F) bump stops to arrest the top plate at specific drop heights and angles.

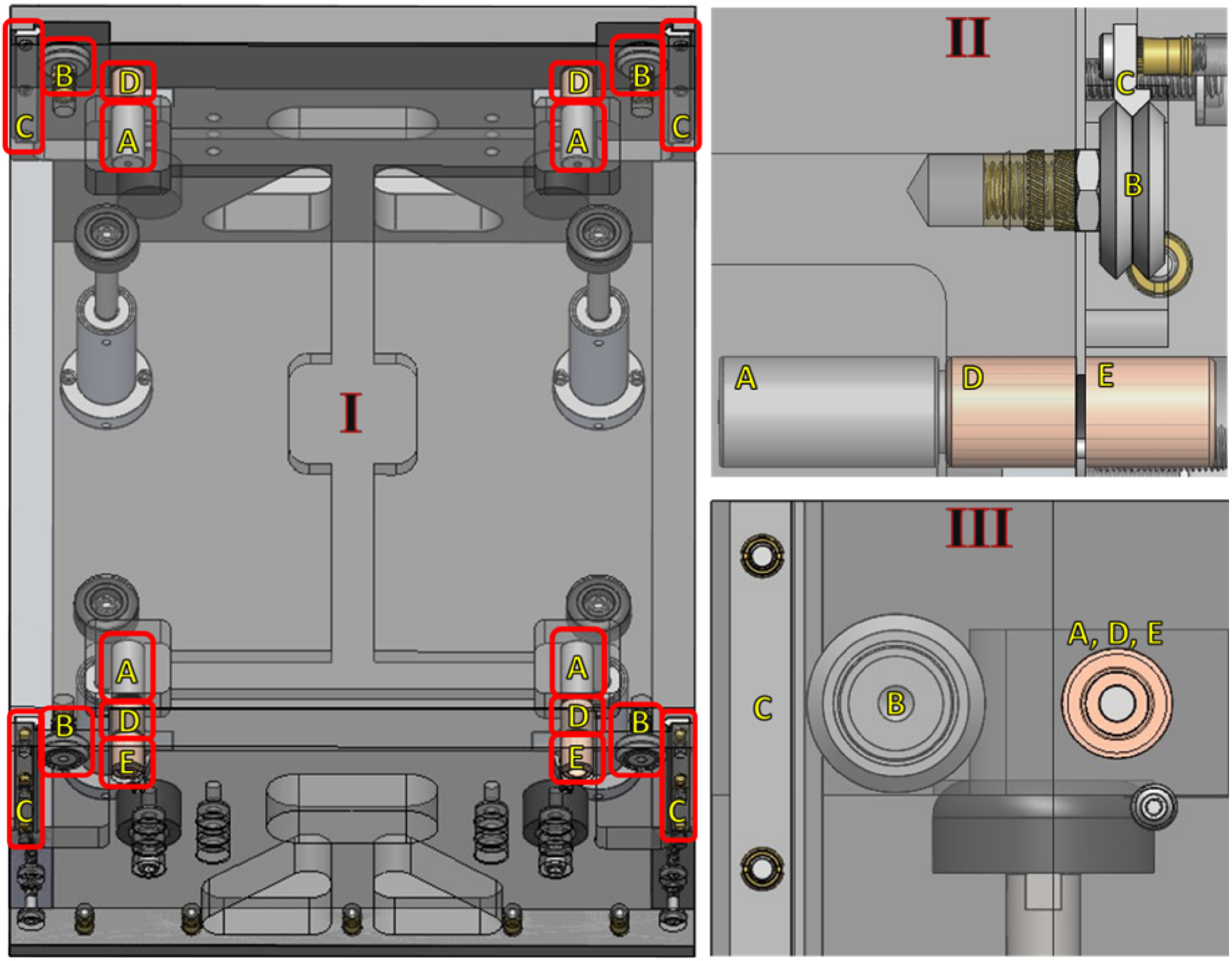

Figure 3

Perturbation Platform system with top plate motion control components revealed. Three views I) top view, II) top view detail of solenoid and roller components and III) end view detail of solenoid and roller components. Individual components: A) sealed linear solenoid, B) V-groove track roller, C) V-groove rail, D) top plate brass insert for solenoid mount and pin support, and E) end plate brass insert for pin support.

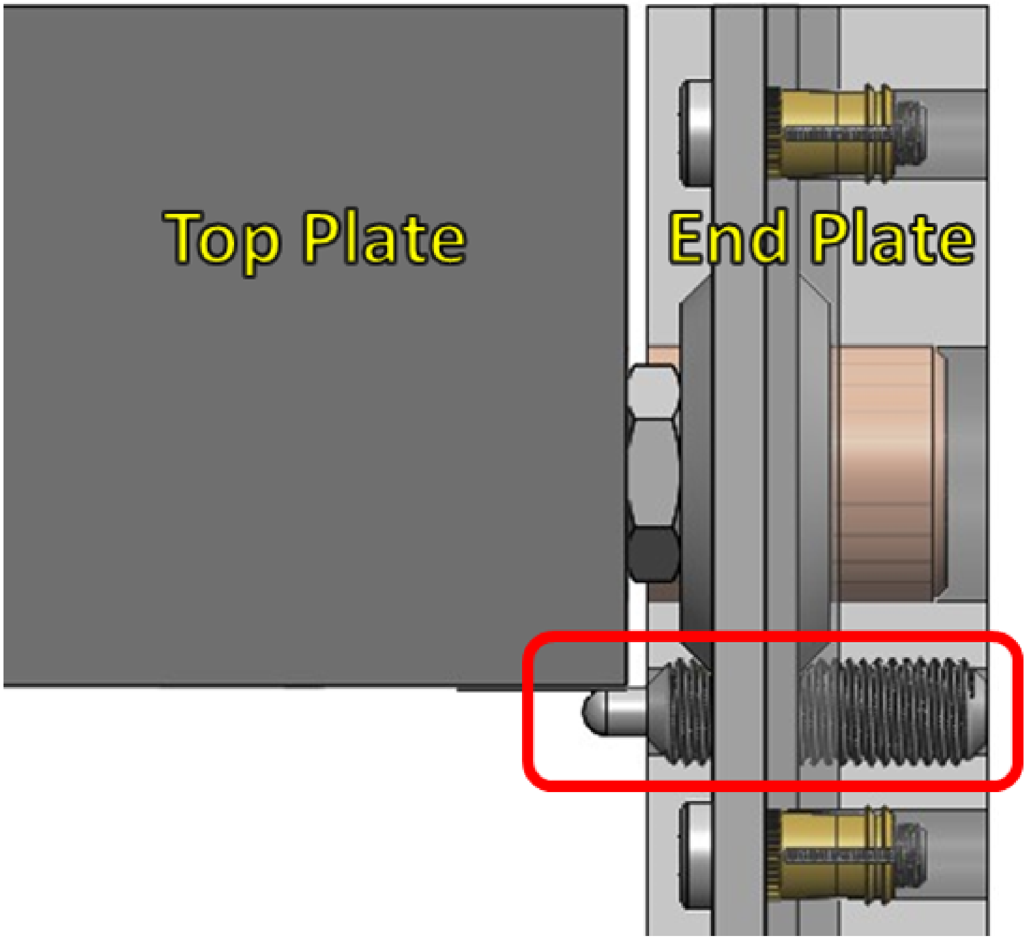

Figure 4

Detail of spring pin support system. Spring pin hardware outlined.

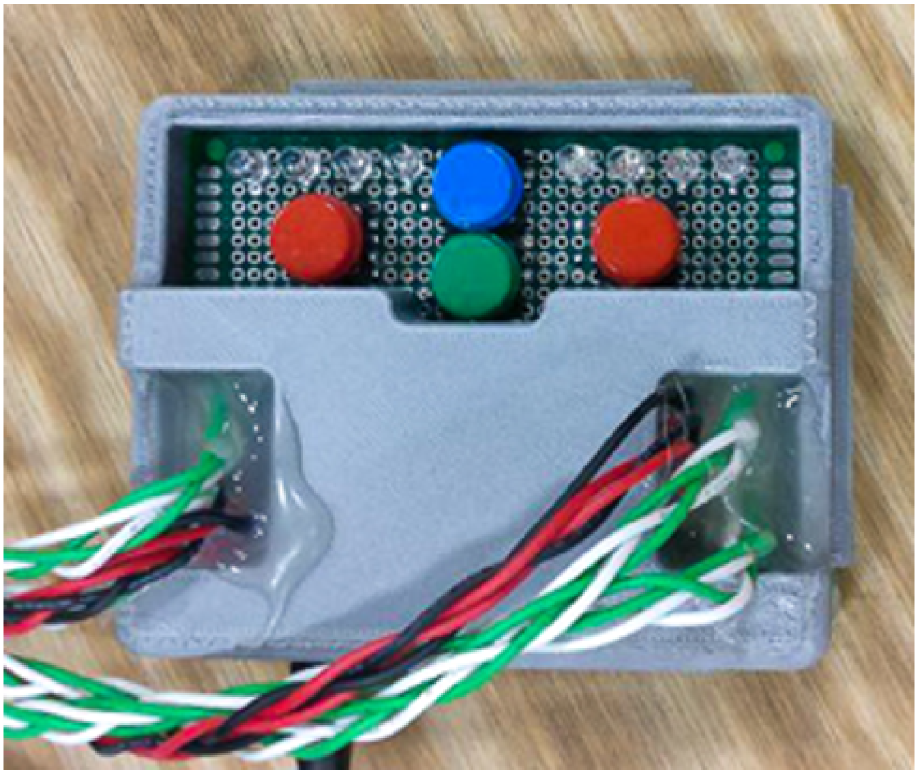

Figure 5

Hand-held controller.

Figure 6

Different configurations available. A) left drop, B) right drop, C) left evert, D) left invert, E) right invert, F) right evert, G) both invert, and H) both evert. Not pictured but available are both up, and both drop.

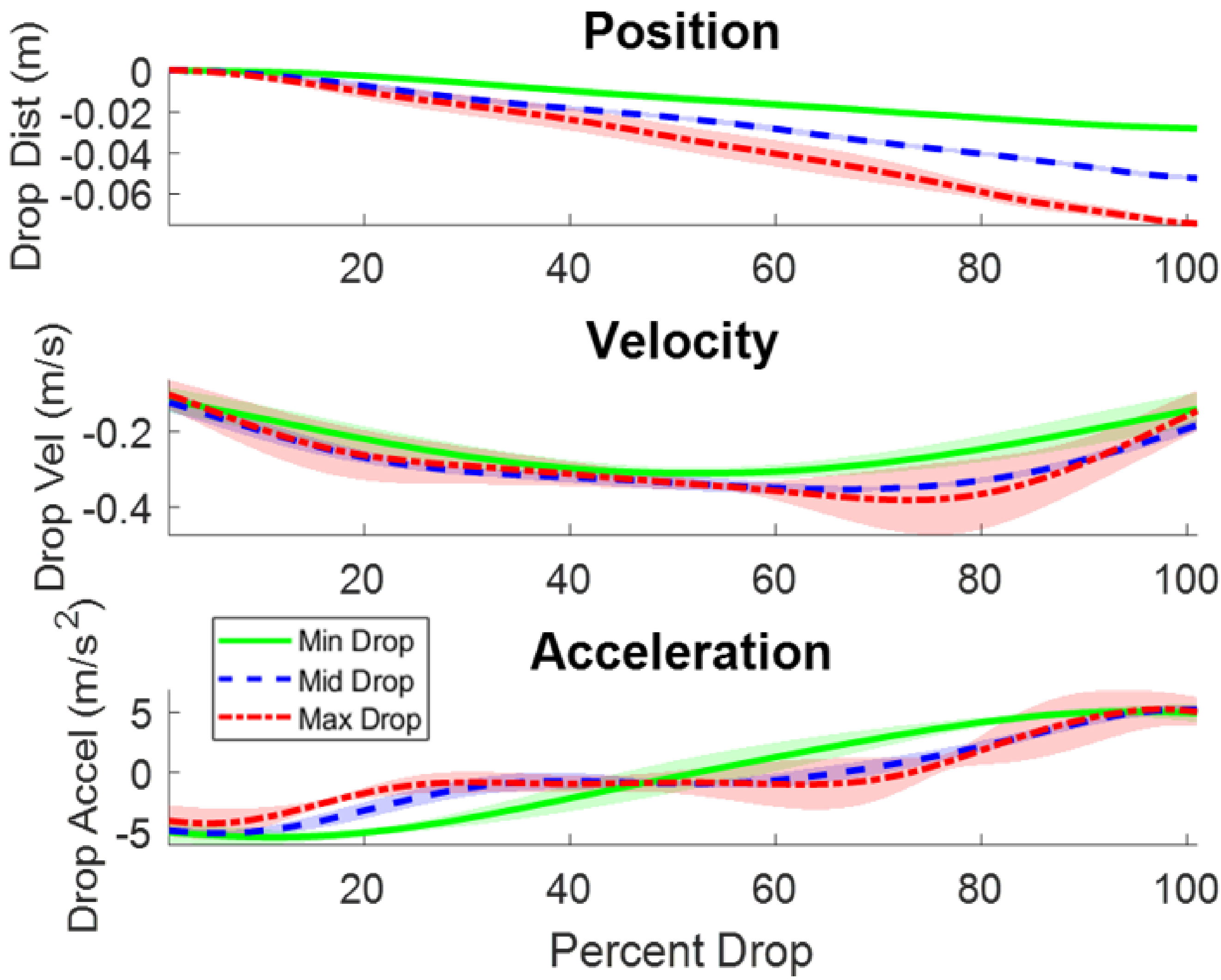

Figure 7

Results of Perturbation Platform System testing for the three straight drop levels. The y-axes show the height velocity and acceleration during the drops. The x-axis shows the normalized time from 0-100% of the drop events. Shaded regions around the lines represent standard deviation over the five repeated drops at each height.