

# Preliminary Evaluation of a Wearable Thruster for Arresting Backwards Falls

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**Abstract**—This paper presents preliminary results assessing the efficacy of a backpack-worn cold-gas thruster to potentially arrest impending backwards falls. Specifically, a nitrogen-based cold gas thruster system was integrated into a backpack-worn prototype device, and experiments were conducted to assess the effect of the wearable device on backwards falls. Although the device is eventually intended for individuals at fall risk, these preliminary experiments were conducted on three healthy subjects. The experiments compared each subject’s ability to recover from an impending fall with and without assistance from the thruster. Results suggest that the likelihood of a fall was substantially reduced with the thruster assistance.

## I. INTRODUCTION

Falls are the leading cause of injury-related death, particularly in elderly people. Over 2.8 million adults 65 years and older in the US reported fall-related injuries in 2014 [1]. These injuries ranged from minor lesions and bruises to life-threatening hip fractures and traumatic brain injuries, with 27,000 resulting in death annually [1,2]. Falls are a widespread hazard that lead to severe and fatal injuries, and fear of falling can lead to loss of independence [3]. In-home fall prevention solutions, including handrails, non-slip flooring, and improved lighting, are common. The majority of falls, however, occur in less controlled spaces such as shopping centers and sidewalks; as such, versatile fall-prevention approaches for unstructured environments are needed [4].

This paper explores the potential value of providing a corrective thrust force generated by a backpack-worn cold-gas thruster to arrest an impending fall and restore balance to an individual. Prior work by the authors indicated a backpack sized thruster could provide a thrust impulse capable of arresting an impending fall and returning the individual to an upright position [21,22]. In this paper, the authors have configured a thruster prototype into a backpack-wearable device, and tested the prospective efficacy of the thruster in arresting backward falls on three healthy individuals, each artificially impaired to better reflect a fall-risk population. This paper describes the wearable thruster prototype, describes the human-subject experiments performed by the authors to assess prospective efficacy, and presents the results of these experiments.

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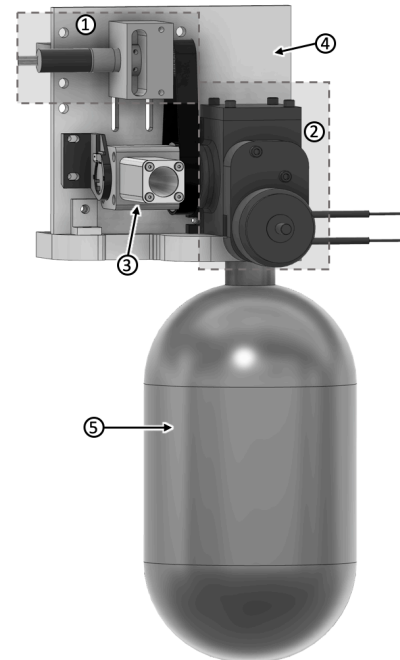


Fig. 1: CAD model of thruster prototype showing: 1) nozzle servo system, 2) custom poppet valve, 3) thruster nozzle, 4) mounting plate, 5) carbon fiber tank.

## II. THRUSTER PROTOTYPE

The thruster prototype and its constituent components are shown in a solid model in Fig. 1. The design of the thruster prototype was described in detail in [21, 22], and is described only briefly here. The prototype used in this paper is a modified version of the designs presented previously, with major modification associated with rendering it as a backpack-wearable device, and also with updates to the solenoid-actuated valve and nozzle with servo system to improve reliability and functionality. The carbon-fiber compressed gas tank has a volume of 1 L and is initially charged with nitrogen gas to a pressure of 10 MPa (1500 psi). When energized by the controller, the solenoid opens the poppet valve, which releases the compressed gas through the nozzle. The resulting thrust impulse provides a decaying thrust pulse with an initial thrust of approximately 350 N,

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which decays to zero over a period of approximately 700 ms. See [21] for the specific thrust characteristics. The thruster also includes an on-board embedded system that employs a six-axis IMU for sensing, as well as control electronics for the servo control axis and actuation of the poppet valve. The assembled thruster prototype (as shown in Fig. 1 without backpack) has a total mass of 2 kg and a volumetric envelope of 30 cm x 18 cm x 11 cm.

In prior works, the thruster prototype was mounted to a human-scale rocking block and experimentally tested for efficacy. In this work, the thruster was tested on human subjects, and as such was configured into a backpack-wearable version, as shown in Fig. 2. In the wearable version, the thruster was affixed to a 15 cm x 15 cm x 0.5 cm aluminum plate, which was in turn mounted onto a 3D-printed backplate, the latter of which was form-fitted to the curvature of a human back. The plastic backplate was then affixed to a user via three nylon straps: two shoulder straps and a chest strap, donned in a similar fashion to a tight-fitting backpack. In order to enhance the safety of the wearer, a shroud and tank protector pouch were affixed onto the aluminum plate. The shroud consisted of a 3 mm thick piece of nylon plastic bent into an upside-down “U” shape, affixed with brackets and extending approximately 10 cm from the backplate. A paintball tank safety pouch was purchased and affixed to the back plate, such that if the tank were to disconnect from the thruster system, it would remain tethered to the backplate. Finally, a quick-connect fitting and manually-switched ball valve were fitted between the 1L carbon-fiber tank and poppet valve inlet so that the thruster tank could be easily recharged between experimental trials. The wearable version and associated components are shown in Fig. 2. The fully assembled backpack as shown in Fig. 2, with protective features and quick-connect fittings, has a mass of 5 kg.

### III. EXPERIMENTAL ASSESSMENT

In order to ascertain the prospective efficacy of the thruster in arresting backward falls, a set of experiments was conducted in which three healthy subjects were released from various states of imbalance, and their ensuing movement was recorded for three experimental cases: 1) without wearing the thruster; 2) while wearing the thruster, but without thruster assistance; and 3) with thruster assistance. These three cases are referred to as control, inactive, and active trials, respectively. For each case, each subject was released from five different inclination angles three times each, for a total of 15 trials. Therefore, across all three cases, each subject was released into a total of 45 falls. In order to emulate the impaired reaction of a fall-risk population, each subject wore ankle weights and an elastic band around his or her legs, as described below. Each subject wore a safety harness, which was instrumented with a load cell to measure harness force. Each subject was also fitted with motion capture markers, which recorded his or her movement following the release.

Since the primary objective of this investigation was to assess the prospective value of a thruster in arresting impending falls, rather than employ a state-based controller for the thruster, the authors used a simpler means of initiating

the thruster. Namely, for the cases in which the thruster was active, it was initiated 0.1 s following each release. Although this approach is not realistic for a real fall scenario (in which a fall would need to be detected based on measured data), this simplistic controller is sufficient to determine in this preliminary testing the extent to which a thruster might offer benefit to a falling individual. A more detailed description of the fall experiments follows.

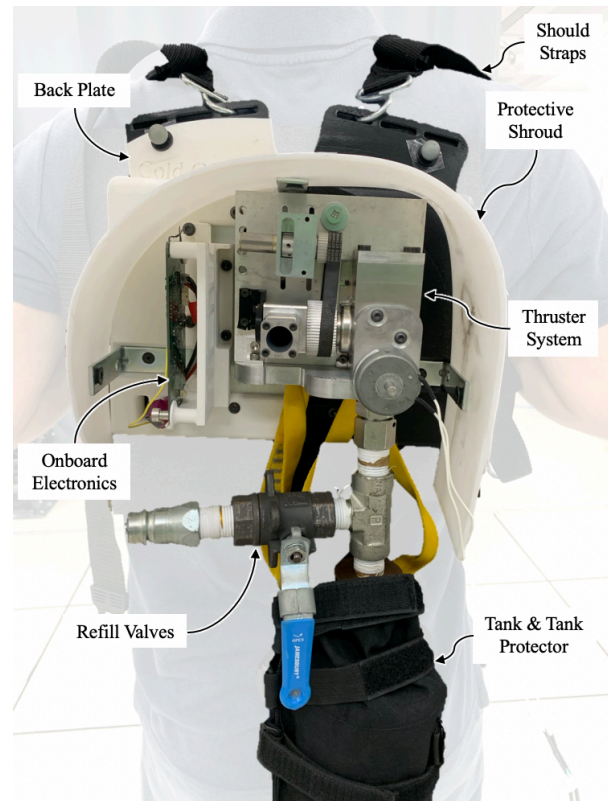


Fig. 2: Photo of the backpack-wearable thruster prototype, with major components labeled. Note that the protective shroud and tank cover were employed to enhance human-subject safety, and the quick-connect and refill valve were employed to expedite recharge of the 1L tank between experimental trials.

#### A. Experimental Setup

The essential experimental setup is diagrammed in Fig. 3 and shown in video frames in Fig. 4. The experimental setup consists of a harness system; an anchor and tethering system with an inline electromagnet for quick release; and the thruster system and accompanying fill tank. The harness system used an overhead linear sliding rail with a hard stop 3.5 meters from the participant’s starting location. The harness was connected to the rail slider via climbing rope and camming mechanism, which enabled adjustment of harness slack. A load cell was arranged in-line with the rope with its distal end connected to a 3-point upper body harness, measuring the force of suspension.

Falls were generated by releasing the subjects from a backward-leaning posture using a tether and electromagnet, as depicted in Fig. 3. Specifically, subjects were tethered from the anterior aspect of the harness to an anchoring pole (bolted into the lab floor). Subjects leaned backward against the tether

at various initial angles, and were unexpectedly released to initiate each trial.

Rather than involve individuals at fall risk as experimental participants, it was deemed more appropriate to conduct this preliminary testing on healthy subjects. Three subjects volunteered for the testing, two male and one female, ranging in age from 21 to 28 years, weight from 54.4 kg to 84 kg, and height from 1.7 m to 1.9 m. Each healthy subject wore 2.3 kg (5 lb) ankle weights, and also a 1000 N/m elastic exercise band around both ankles, both of which reduced each subject’s capacity to hop or take large steps, in effect altering their response to better emulate that of an elderly individual.

A ten-camera motion capture system (Vicon, Oxford GBR) was used with corresponding motion capture markers to record the motion of the subject following each release. Motion capture markers were placed on each subject’s feet, knees, hips, and shoulders using standard marker placement methods. Once the markers were secure, the subject donned an upper body harness. The height of the overhead safety harness was adjusted such that the subject’s knees were approximately 5 cm above the ground when the subject was hanging loosely in the harness.

Each subject’s testing occurred over the course of one session, lasting approximately two hours. The subjects were first briefed and prepared for the control experiment, following which the subject donned the fall prevention thruster and was subjected to the active/inactive thruster testing.

### B. Control, Inactive, and Active Test Cases

As previously mentioned, three cases were tested: 1) a “control” case, in which no backpack was worn; 2) an “inactive” case, in which the thruster was worn but not activated; and 3) an “active” case, in which the thruster provided assistance. Ideally, the control case would be compared directly to the case with thruster assistance; however, subjects could not reasonably be blinded to this case, since in one case the subject was not wearing the thruster backpack while in the others they were. As such, the same set of trials were performed in two separate experiments: 1) a first set of experiments that involved only the control case (i.e., imbalance responses without the backpack, the first test case); and 2) a second set of experiments for which the backpack was worn, and where the thruster was randomly either active or inactive (the second and third test cases). In this manner, the control case can be compared to the inactive case, to gauge the extent to which the inactive backpack affects balance recovery; and subsequently, the inactive case can be compared to the active case, to gauge the extent to which thruster thrust affects balance recovery in a blinded and randomized presentation of both “treatments.” Notably, the blind randomization between active and inactive treatments for each trial prevented the subject from learning to rely on the thruster, as in 50% of cases the thruster would not fire. Additionally, given the active and inactive cases were evenly dispersed through the total duration of testing, fatigue effects were controlled for. Video frames from one of the control trials are shown in Fig. 4 frames (a) through (d), while video frames from one of the active trials are shown in Fig. 4 frames

(e) through (h). Videos of these trials are included in the supplementary material submitted with this paper.

### C. Data Processing

Position data from the motion capture markers was used to determine the angle from vertical of the subject’s center of mass, using an offset from the initial calibration trials. Specifically, the subject’s center of mass angle was taken to be the vector between the subject’s foot and 20% of the distance from the hip markers to the shoulder markers, which approximated the location of the subject’s center of mass. This vector was then compared to the vertical angle in the sagittal plane to record the subject center of mass angle.

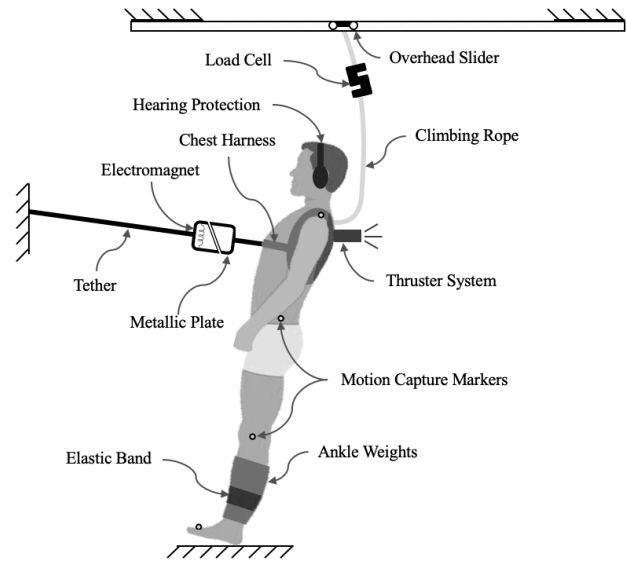


Fig. 3: Experimental setup diagram.

## IV. RESULTS

### A. Fall Metric

During each trial, subjects reported if they felt the trial would have resulted in a fall in the absence of the overhead harness system. Figure 5 shows representative force profiles recorded for three perceived falls (red traces) and for three perceived recoveries (blue traces). Although the initial harness loading is similar between perceived falls and recoveries, the impulse associated with the perceived falls is substantially larger than for the perceived recoveries. Figure 6 compares harness impulse for each trial after a given transience period following fall initiation.

Though data from both the fall and recovery cases follow a similar trend, the distinction between perceived falls versus recoveries becomes clearer when the impulse is computed with a longer delay following the fall initiation. Based on this data, the authors chose to use a delay of 2 seconds following the experiment start to compute the harness impulse, in which case an impulse of 75 N-s provides a strong correlation to the threshold between perceived falls and recoveries.

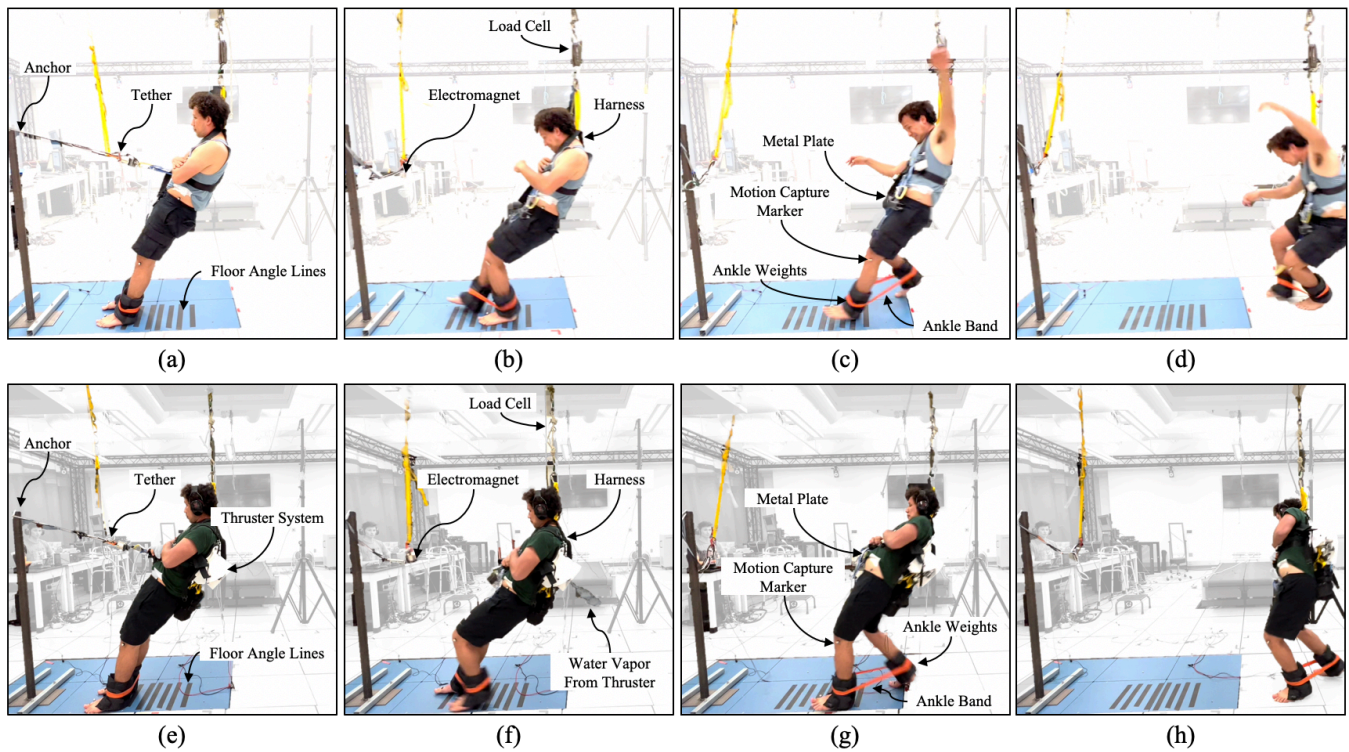


Fig. 4. (a-d) Control fall case (i.e., without wearing thruster) and (e-h) Active thruster case (i.e., with thruster assistance); a & e) Pre-Release b & f) First Step c & g) Recovery Step d) Fall Recorded h) Recovery

This correlation is indicated in Fig. 7, which shows the distribution of data associated with perceived falls, along with the distribution of data associated with perceived recoveries. For purposes of this paper, one can assume that an impulse greater than 75 N-s, 2 s after the release event, is a strong indication that without the safety harness, a fall would have likely occurred.

### B. Control versus Inactive Cases

Fig. 8 shows the aggregate impulse (computed 2 s following release) across subjects and trials for the control case relative to the same aggregate impulse for the inactive trials (i.e., trials without the backpack, and also for the trials when the backpack was worn, but no thrust was generated). Although the distribution of impulse is slightly different between the two cases, the medians are nearly identical, and a Wilcoxon Rank-Sum Test indicates no statistical difference between the two cases. Therefore, one can reasonably assume that the “inactive” case reflects the same outcomes as the case without wearing a backpack.

### C. Active versus Control Cases

Fig. 9 shows the aggregate impulse (computed 2 s following release) across subjects and trials for the active thruster case and for the control trials (i.e., trials with thruster backpack assistance and trials without a backpack). The assistance from the backpack reduced the measured impulse; the median impulse in the control case was 130 N-s, while the median impulse in the thruster active case was 10 N-s (well under the perceived fall impulse of 75 N-s). In the case of thruster assistance, nearly all cases corresponded to a perceived recovery, while only outliers corresponded to a perceived fall.

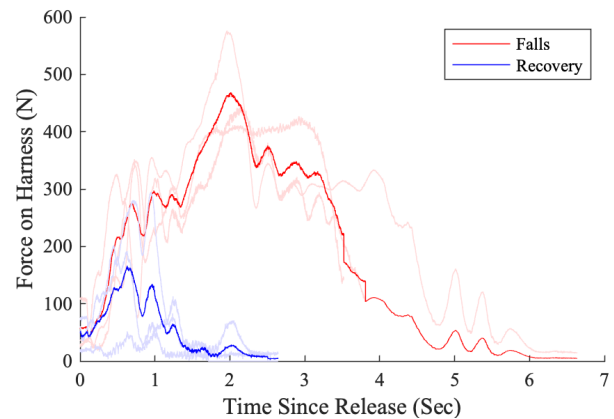


Fig. 5: Representative harness force profiles for perceived falls (red) and perceived recoveries (blue).

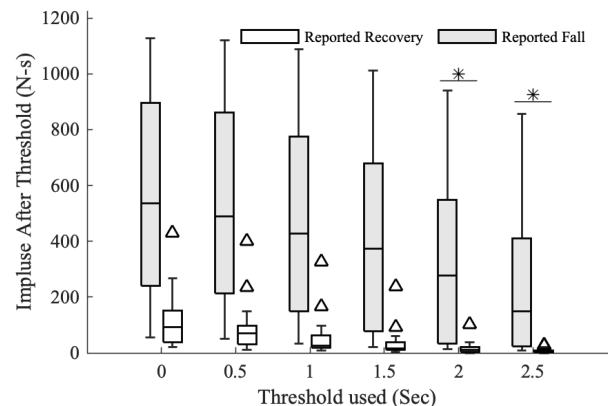


Fig. 6: Harness impulse for perceived falls (grey boxes) and perceived recoveries (white boxes), as a function of delay following the release event (e.g., for a 1 s delay, the impulse is only calculated starting 1 s following the release event).

## V. DISCUSSION

This study indicates that a fall prevention thruster may have significant promise in reducing the rate and severity of balance loss for backwards falls. Furthermore, there was no statistically significant effect of wearing an inactive thruster on fall risk. These results point to potential benefits of wearing the active device. While these results are promising, the device was tested on healthy individuals in a well-controlled laboratory setting. Further, the system did not use a realistic controller, which will require a means of fall detection. Additionally, the fall metric that was chosen, impulse after two seconds, does not account for loading of the harness in the first two seconds. Notably, the same conclusion would have been reached if the maximum load on the harness had been used as the fall metric. Therefore, although the results are promising, further work is required to more clearly establish the potential value of this device. While these conclusions strongly indicate a benefit to the use of a fall prevention thruster for purposes of arresting falls, work remains to be done to develop the device from its current level of technological readiness, to one that renders it suitable for practical use.

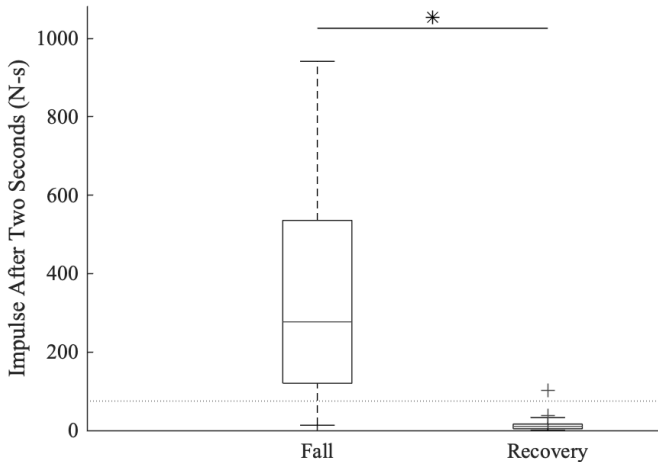


Fig. 7: Perceived falls versus recoveries based on the measured harness impulse 2 s following the release event. The distinction between falls and recoveries is indicated by an impulse cut-off of 80 N-s.

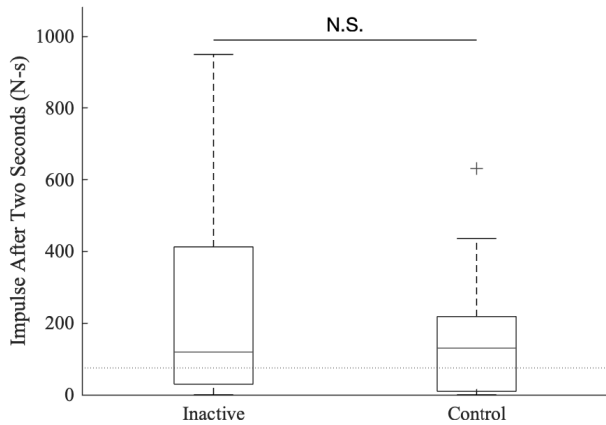


Fig. 8: Safety harness impulse for inactive thruster versus control case (i.e., without backpack device). The dotted line indicates the impulse that most likely corresponds to a fall (see Fig. 7). There was no statistically significant difference in the results, indicating that the backpack (when inactive) did not notably affect the participants' ability to recover balance.

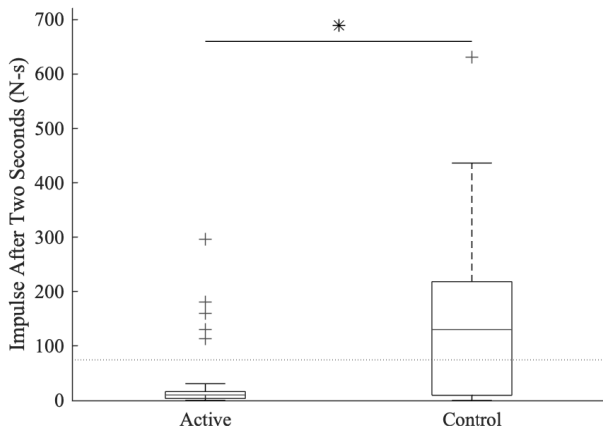


Fig. 9: Safety harness impulse for thruster assistance versus control case (i.e., without backpack device). The dotted line indicates the impulse that most likely corresponds to a fall (see Fig. 7). Assistance from the thruster resulted in a more than tenfold decrease in median impulse.

## VI. FUTURE WORK

The thruster described herein appears to provide substantial promise as a device that can potentially arrest impending falls in a fall-risk population. Significant future work remains to be done, in particular with regard to developing and testing a control algorithm capable of robustly detecting falls outside of well controlled experiments and providing appropriate response to human wearers. Additionally, while the majority of falls that occur are backwards falls, a system which is capable of addressing omnidirectional falls is also a potentially important topic of future work. Finally, the hardware used in this device consisted largely of components that were optimized for ease of modification and cost of assembly. Additional work remains to be done to reduce weight as well as to enhance the form factor to ensure that the backpack-worn device is well suited to everyday use.

## REFERENCES

- [1] Ambrose, A. F., Paul, G., and Hausdorff, J. M., 2013, "Risk factors for falls among older adults: a review of the literature," *Maturitas*, 75(1), pp. 51–61, doi: 10.1016/j.maturitas.2013.02.009.
- [2] Bergen, G., Stevens, M. R., and Burns, E. R., 2016, "Falls and Fall Injuries Among Adults Aged  $\geq 65$  Years — United States, 2014," *MMWR Morb. Mortal. Wkly. Rep.*, 65(37), pp. 993–998, doi: 10.15585/mmwr.mm6537a2.
- [3] Lockhart, T. E., Smith, J. L., and Woldstad, J. C., 2005, "Effects of Aging on the Biomechanics of Slips and Falls," *Hum. Factors J. Hum. Factors Ergon. Soc.*, 47(4), pp. 708–729, doi: 10.1518/001872005775571014.
- [4] Lord, S. R., Ward, J. A., Williams, P., and Anstey, K. J., 1993, "An epidemiological study of falls in older community-dwelling women: the Randwick falls and fractures study," *Aust. J. Public Health*, 17(3), pp. 240–245, doi: 10.1111/j.1753-6405.1993.tb00143.x.
- [5] Hamza, M. F., Ghazilla, R. A. R., Muhammad, B. B., and Yap, H. J., 2020, "Balance and stability issues in lower extremity exoskeletons: A systematic review," *Biocybernetics and Biomedical Engineering*, 40(4), pp. 1666–1679, doi: 10.1016/J.BBE.2020.09.004.

- [7] Tucker, M.R., Olivier, J., Pagel, A., et al., 2015, "Control strategies for active lower extremity prosthetics and orthotics: a review," *J Neuroeng. Rehabil*, 12(1), <https://doi.org/10.1186/1743-0003-12-1>
- [8] T. Yan, M. Cempini, C. M. Oddo, and N. Vitiello, 2015, "Review of assistive strategies in powered lower-limb orthoses and exoskeletons," *Rob. Auton. Syst.*, vol. 64, pp. 120–136, doi: 10.1016/j.robot.2014.09.032.
- [9] Wang, S., et al., 2015, "Design and Control of the MINDWALKER Exoskeleton," *IEEE Trans. Neural Syst. Rehabil. Eng.*, 23(2), pp. 277–286, doi: 10.1109/TNSRE.2014.2365697.
- [10] Zhang, T., Tran, M., and Huang, H., 2018, "Design and experimental verification of hip exoskeleton with balance capacities for walking assistance," *IEEE/ASME Trans. Mechatronics*, 23(1), pp. 274–285, doi: 10.1109/TMECH.2018.2790358.
- [11] Ugurlu, B., et al., 2016, "Variable Ankle Stiffness Improves Balance Control: Experiments on a Bipedal Exoskeleton," *IEEE/ASME Trans. Mechatronics*, 21(1), pp. 79–87, doi: 10.1109/TMECH.2015.2448932.
- [12] Fasola, J., Vouga, T., Baud, R., Bleuler, H., and Bouri, M., 2019, "Balance control strategies during standing in a locked-ankle passive exoskeleton," *IEEE Int. Conf. Rehabil. Robot.*, pp. 593–598, doi: 10.1109/ICORR.2019.8779500.
- [13] Huynh, V., Bidard, C., and Chevallereau, C., 2018, "Balance control for an active leg exoskeleton based on human balance strategies," *Mech. Mach. Sci.*, 48, pp. 197–211, doi: 10.1007/978-3-319-59972-4\_15.
- [14] Di, P., et al., 2016, "Fall detection and prevention control using walking-aid cane robot," *IEEE/ASME Trans. Mechatronics*, 21(2), pp. 625–637, doi: 10.1109/TMECH.2015.2477996.
- [15] Vallery, H., Bögel, A., O'Brien, C. and Rienen, R., 2012, "Cooperative Control Design for Robot-Assisted Balance During Gait," *Auto.*, 60 (11), pp. 715–720, doi: 10.1524/auto.2012.1041.
- [16] Chiu, J., and Goswami, A., 2014, "Design of a Wearable Scissored-Pair Control Moment Gyroscope (SP-CMG) for Human Balance Assist," Volume 5A: 38th Mechanisms and Robotics Conference, Buffalo, NY, USA, p. V05AT08A023, doi: 10.1115/DETC2014-35539.
- [17] Lemus, D., van Frankenhuyzen, J., and Vallery, H., 2017, "Design and Evaluation of a Balance Assistance Control Moment Gyroscope," *J. Mech. Robot.*, 9(5), p. 051007, doi: 10.1115/1.4037255.
- [18] Li, D., and Vallery, H., 2012, "Gyroscopic assistance for human balance," 12th IEEE International Workshop on Advanced Motion Control (AMC), Sarajevo, Bosnia and Herzegovina, pp. 1–6, doi: 10.1109/AMC.2012.6197144.
- [19] Matsuzaki, R., and Fujimoto, Y., 2013, "Walking assist device using Control Moment Gyroscopes," *IECON 2013 – 39th Annual Conference of the IEEE Industrial Electronics Society*, Vienna, Austria, pp. 6581–6586, doi: 10.1109/IECON.2013.6700220.
- [20] Oya, H., and Fujimoto, Y., 2017, "Preliminary experiments for postural control using wearable-CMG," *Proceedings IECON 2017 – 43rd Annual Conference of the IEEE Industrial Electronics Society*, pp. 7602–7607, doi: 10.1109/IECON.2017.8217332.
- [21] Lemus, D., et al., 2020, "Controller synthesis and clinical exploration of wearable gyroscopic actuators to support human balance," *Sci. Rep.*, 10(1), pp. 1–15, doi: 10.1038/s41598-020-66760-w.
- [22] Baimyshev, A., Finn-Henry, M. and Goldfarb, M., 2022. Feasibility of a Wearable Cold-Gas Thruster for Fall Prevention. *Journal of Dynamic Systems, Measurement, and Control*, 144(8), p.084501.
- [23] Finn-Henry, M., Baimyshev, A., and Goldfarb, M., 2020, "Feasibility Study of a Fall Prevention Cold Gas Thruster," 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob), pp. 611–616, doi: 10.1109/BioRob49111.2020.9224425.