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ORIGINAL ARTICLE

The underestimation of speed perception while walking in virtual reality with bodyweight unloading

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Abstract

As space agencies prepare for long-duration missions, such as establishing a permanent moon base, maintaining astronauts' physical and mental health becomes crucial. Exercise is known to counteract the adverse effects of space travel, and virtual reality (VR) has the potential to enhance the psychological well-being of crew members. This study aimed to investigate the impact of bodyweight unloading on speed perception during treadmill walking in a VR environment. Eighteen participants walked on an AlterG treadmill while wearing a VR headset that displayed a moving virtual outdoor environment. The treadmill simulated different bodyweight conditions (100%, 60%, and 20%) to represent Earth's gravity, intermediate, and lunar gravity, respectively. A staircase method was used to determine participants' estimated threshold speed for perceiving visual speed equivalence. The results revealed that in all conditions, participants consistently underestimated their walking speed compared to the visual scene speed. No significant differences were found in estimated threshold speeds between the unloading conditions. Individual responses varied, possibly due to biomechanical differences and personal preferences. Participants reported no motion sickness symptoms, likely attributed to the short duration of speed mismatches and the use of high-resolution and high-refresh-rate VR equipment. This study provides insights into the combination of VR and treadmill walking, suggesting the importance of individual customization to enhance user experience and prevent motion sickness.

Keywords Virtual reality · Perception · Walking · Speed · Unloading · Treadmill

1 Introduction

With the emergence of the National Aeronautics and Space Administration's (NASA) Artemis program, humans are set to return to the moon with the intent of not just visiting but staying permanently. NASA, along with other governmental and private space programs, is preparing to establish a permanent moon base that would see astronauts living on the moon's surface for long durations. This is a difficult environment for humans to thrive in, both physically and psychologically. With the moon's gravity being only 16% of Earth's, muscles can atrophy, and bones lose density unless effective countermeasures are put in place (Stavnichuk et al. 2020; Lee et al. 2022). Humanity's 30+ years of continuous presence in low earth orbit has demonstrated that daily exercise is a key countermeasure for keeping the body and mind healthy (Weber et al. 2020). Experience has also shown the importance of astronauts' psychological wellness as spaceflight can be a monotonous and isolating experience (Arone et al. 2021).

Innovative practices must be implemented to keep astronauts' bodies and minds healthy during these long-duration space missions. With the upcoming moon missions, there is a gap in knowledge about how long lengths of time on the moon will affect crew members' mental health and wellness. There will be increased distance from Earth, potential blackout periods of no communication, and increasingly longer missions (1–3 years) to simulate the length of a future Mars mission. One proposed way to effectively exercise and provide psychological enrichment simultaneously is by having crew members run on a treadmill while being immersed in an enriching virtual environment. A virtual reality (VR)

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environment could be provided to crew members by wearing a head-mounted display (HMD) virtual reality device, which would display a scene from Earth and would match the speed of the treadmill. This could prevent boredom during the crew member's several hours of exercise per day and allow them to virtually run through different Earth environments such as a peaceful virtual nature scene or a bustling urban city. Exercising while viewing scenes such as these has shown to promote relaxation and decrease stress both psychologically and physiologically (Annerstedt et al. 2013; Anderson et al. 2017). This could provide comfort from being in a familiar visual and auditory environment and is a plausible measure in preventing mental state deterioration in astronauts (Salamon et al. 2018). This combination of technology while exercising (also known as exergaming) has been tested on the International Space Station (ISS) while cycling for the sole purpose of psychological enrichment (Bénard 2021).

This combination of being immersed in VR while walking on a treadmill has also been demonstrated in a rehabilitation setting where different optic flow speeds did not significantly impact motion sickness levels when walking on a Lokomat gait exoskeleton (De Keersmaecker et al. 2020). However, another attempt at combining VR with an omnidirectional walking platform for rehabilitation purposes resulted in 71% of participants having mild to moderate cybersickness symptoms (Soon et al. 2023). In that study, the video playback speed was set to play in relation with the subjects walking speed, with subjects giving the feedback that they felt a mismatch between these two speeds despite them being equal, leading to their onset of cybersickness.

For a potential lunar application, to provide the most realistic scenario and prevent similar problems with motion sickness, the speed of the VR scene would need to match the user's perception of their ambulatory speed. In research on Earth using standard treadmills, subjects require a faster visual speed to perceive it as equal to their own speed (Banton et al. 2005). This is exaggerated for faster running speeds, where subjects underestimate their running speed by an average of 31% (Caramenti et al. 2018). This speed discrepancy may be altered in lunar gravity due to less somatosensory input from the soles of the feet, changes in biomechanics, and altered proprioception from the lower legs (Margaria 1973; Ferrè et al. 2015; Ozdemir et al. 2018). These alterations have been investigated while running in simulated lunar gravity on a parabolic flight which showed a walk-run transition speed of 3.1 miles per hour (mph) compared to the average on Earth of 4.5 mph, indicating major differences in biomechanics between the two environments (De Witt et al. 2014). This speed discrepancy in altered gravity conditions needs to be understood further as it may impact a person's perception of their walking speed as it relates to a moving VR scene, therefore increasing the risk of motion sickness.

Therefore, this pilot study explores the question, 'How does bodyweight unloading affect speed perception while walking?'. This study has two aims, the first is to compare our results on a possible speed discrepancy to previous findings on standard bodyweight treadmills, and the second is to quantify the average speed discrepancy for different unloading conditions to determine if there is a significant difference in speed perception in different unloading environments.

2 Methods

2.1 Study sample

Eighteen subjects (9 female, 9 male) with a mean age of 24.1 (±4.4 SD) participated in the experiment. They were naïve to the purpose of the study, had 20/20 vision or corrected vision using contact lenses, had no injuries that could affect their ability to walk for an extended amount of time, and had no known susceptibility to motion sickness. Potential participants were excluded if they were pregnant, had a height below 4'8" or above 6'4", or weighed less than 85lbs or above 400lbs due to the treadmill manufacturer restrictions.

All participants gave their informed and written consent prior to their inclusion in the study, which was performed in accordance with the ethical standards specified by the 1964 Declaration of Helsinki and approved by the Institutional Review Board of the University of Houston.

2.2 Experimental design

As parabolic flights are inaccessible, expensive, and only provide 20–30 s of lunar gravity at a time with intermittent periods of hyper-gravity, it isn't an appropriate analog for longer-duration testing. Therefore, this study utilized a lower-body weight support treadmill (AlterG, Fremont, CA) which can simulate lunar gravity by unloading participants using positive pressure to 20% of their body weight. This is the lower limit of this treadmill and is close to true lunar gravity, which is 16% of Earth's gravity. Participants wore AlterG shorts that ensured an airtight seal through a zippered connection to the pressurized chamber of the treadmill.

2.3 Study procedure

Participants first familiarized themselves with the AlterG treadmill and HMD virtual reality device (Meta Quest 2, Facebook Technologies, LLC, Menlo Park, CA) to ensure a comfortable fit for both. Interpupillary distance was measured and adjustments were made to the lens spacing on the HMD if needed to achieve the best image clarity. The height of the AlterG cockpit was adjusted based on the manufacturer's recommendation to just below the greater trochanter of the femur to allow the greatest range of motion for each participant (AlterG, Inc. 2015). The AlterG then calibrated each participant by weighing them in a quiet stance to provide the correct relative unloading. Participants then wore the HMD while walking in the AlterG (Fig. 1) at 100%, 60%, and 20% of their body weight. The 100% condition represented Earth's gravity, the 20% condition simulated lunar gravity, and the 60% condition was the middle point between those two environments. The order of these conditions was counterbalanced throughout the group and participants took a 10-minute break between each condition to washout any possible aftereffects from bodyweight unloading.

The VR headset displayed a digitally rendered outdoor environment (Octonic VR, New York City, NY), that moved linearly down a walking path. The Meta Quest 2 headset had a stereoscopic LCD display with a refresh rate of up to 90hz and a resolution of 1832 × 1920 per eye in its Fresnel lenses (a collimating lens). This allowed for a wide horizontal field of view (89°) and an immersive virtual experience. The visual scene speed was set at a constant 5 mph (approximately 2.2 m/s) and had subjects walk down a path that simulated an outdoor walk. This scene was reset between conditions for each subject to maintain consistency in the visuals of the environment. Participants were also instructed to direct their gaze straight ahead and avoid any drastic head movements.

A 1-up-1-down staircase method was used to determine the prime-detection threshold for each participant's estimated speed threshold for each unloading environment. This staircase method involved the experimenter manually changing the treadmill speed using the control panel without alerting the participant. The participant could not see the experimenter's hand operating the control panel, and the loud noise from the treadmill's air compressor masked any sound of a button being pressed. The experimenter increased the treadmill speed by 0.2 mph every 15 s (according to a stopwatch) until the participant communicated that they were moving faster than the visual scene (first reversal point). Then, the treadmill speed was decreased by 0.2 mph every 15 s until the participant indicated they were walking slower than the visual scene (second reversal point). This staircase was repeated for 10 reversal points (also known as inversions). These reversal points were then averaged to determine a walking speed that the participant would consider equal to the visual speed (Fig. 2).

The staircase method described increased subject reliability by having participants repeatedly give their perception of speed to ensure consistency and calculate an average from their responses. This staircase method has been previously used in relevant literature regarding speed perception

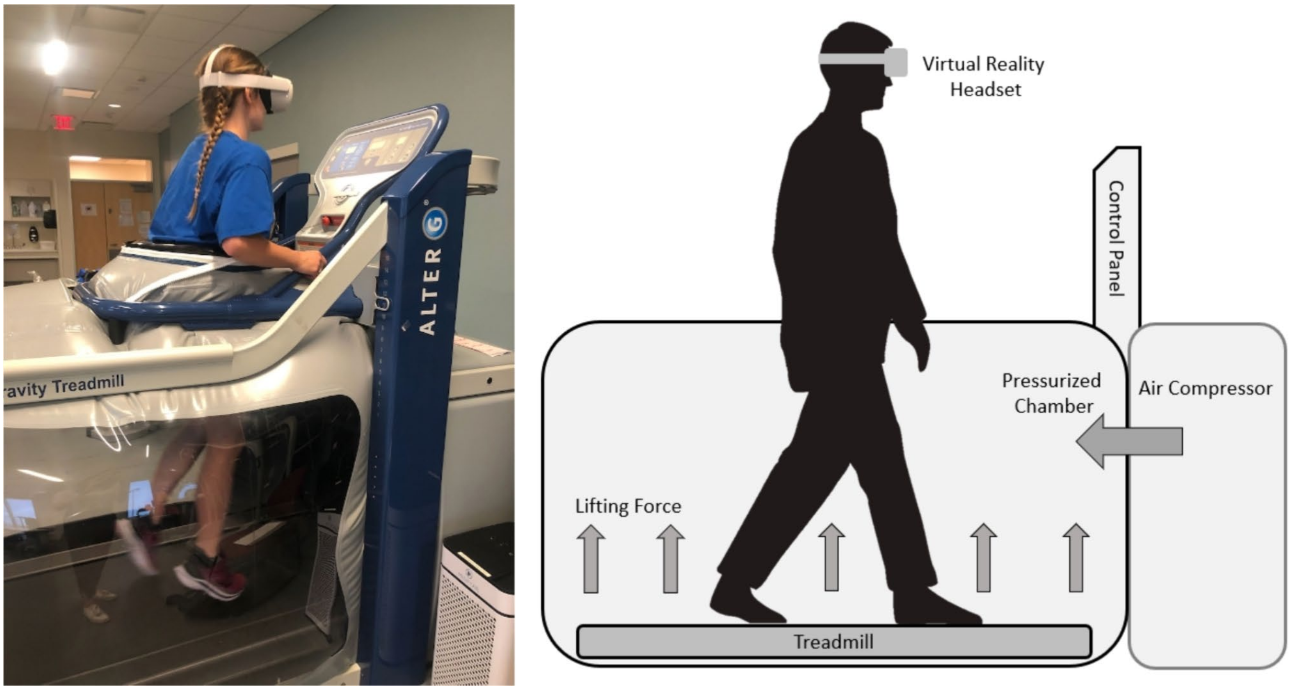

Fig. 1 **a** (left) Experimental setup with a subject in the AlterG treadmill while wearing the virtual reality HMD, **b** (right) Schematic of experimental setup and design of the AlterG treadmill which uses an air compressor to provide positive pressure to a pressurized chamber around the lower body, this positive pressure creates a lifting force that offsets a person's weight

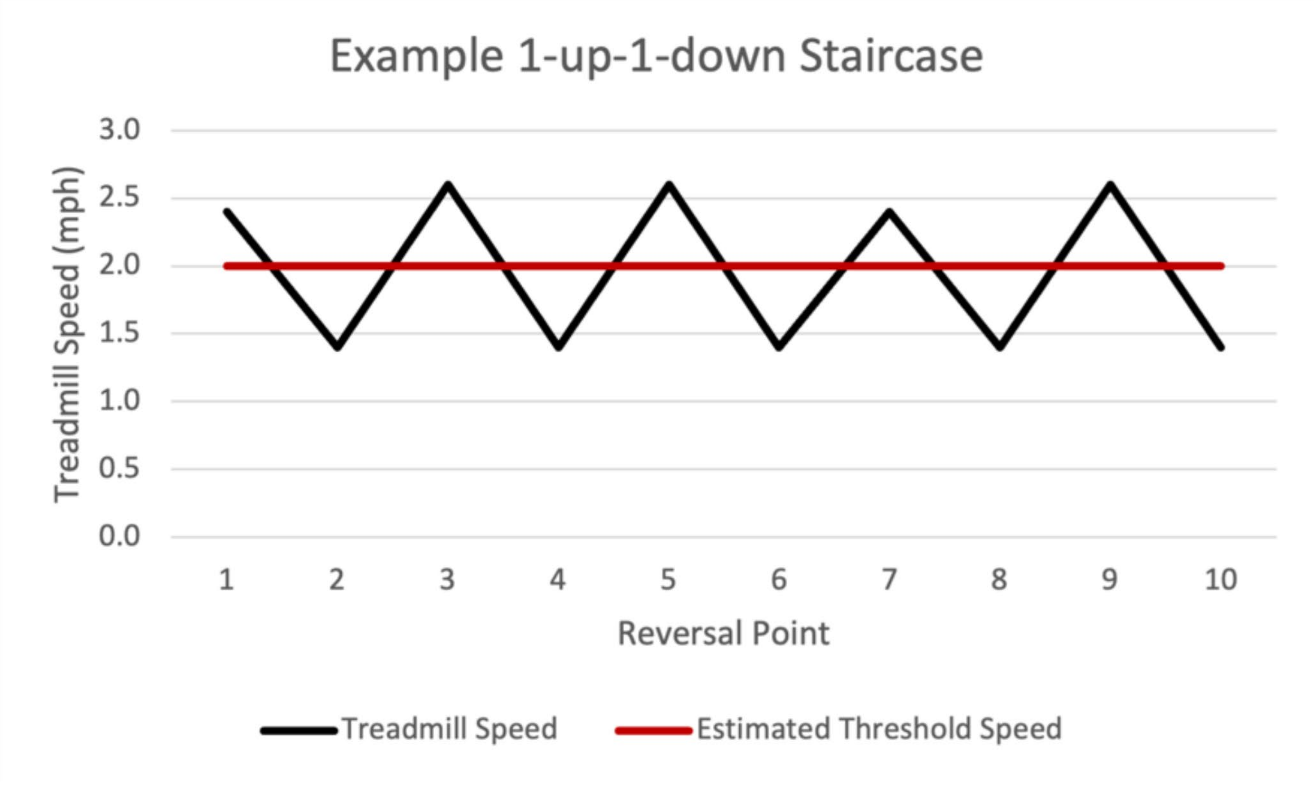

Fig. 2 Representative example of a 1-up-1-down staircase from a study participant showing 10 reversal points/inversions and the resulting estimated threshold speed after averaging all reversal points

as well as other types of sensory perception (Leek 2001; Spielmann et al. 2013; Caramenti et al. 2018).

2.4 Statistical analysis

Participants were placed into one of three categories based on their individual response to increased loading; increased speed, decreased speed, or no change. The range for each participant's reversal points was also calculated by taking the absolute difference between each consecutive high and low reversal point and averaging them to get an average range for the three unloading conditions.

The estimated threshold speeds for all participants were averaged for each condition prior to statistical analysis. A Wilcoxon signed-rank test was used to compare the average estimated threshold speeds to the visual speed. Shaprio-Wilk tests were performed to test for normality, and as the data could not be transformed, a Friedman Test was conducted to compare the estimated threshold speeds of the three unloading conditions. A one-way ANOVA was completed to test for differences in ranges of reversal points between conditions. All statistical tests were performed using SPSS statistical package (IBM, New York, USA) at the level of $p < 0.05$.

Table 1 Comparison of estimated threshold speeds to the constant visual speed in the VR HMD

Condition	Average estimated threshold speed (mph)	Visual speed (mph)
100%	2.25 (±0.38)	5
60%	2.33 (±0.49)	5
20%	2.34 (±0.57)	5

3 Results

3.1 Estimated threshold speeds

One participant was identified as an outlier as they did not fully understand the experimental instructions and their data was therefore removed from the data set prior to statistical analyses. For each of the three unloading conditions (100%, 60%, and 20% body weight) we compared the estimated threshold speed with the virtual environment's constant visual speed. In every condition, participants had an average estimated threshold speed that was lower than the actual visual speed (Table 1). In other words, the visual speed had to be moving almost twice as fast as the treadmill speed for the two to be perceived as matching. A Wilcoxon signed-rank test showed that this difference was significant for every condition, 100% (Z = -3.634, $p < 0.001$), 60% (Z =

-3.627, $p < 0.001$), and 20% (Z = -3.624, $p = < 0.001$). Estimated threshold speeds for each participant can be found in Online Resource 1.

To examine how the unloading environment may have affected the estimated threshold speed, a Friedman Test was performed (as data were not normally distributed). Based on this test, there were no statistically significant differences in estimated threshold speeds between the three conditions, [$\chi2(2) = 1.906$, $p = 0.386$].

3.2 Ranges between reversal points

The average range (difference between the high and low reversal points) for the 100% condition was 1.1 ± 0.8 mph, the 60% condition averaged 1.3 ± 1.0 mph, and the 20% condition averaged 1.4 ± 1.0 mph. As the data were normally distributed a one-way ANOVA was conducted, which revealed no significant differences between the three conditions [$F(2, 48) = 0.45$, $p = 0.640$].

4 Discussion

In this study, participants wore a VR headset while walking on an AlterG treadmill at 100%, 60%, and 20% of their body weight. The VR headset displayed a digitally rendered outdoor environment that moved linearly down a walking path, and a 1-up-1-down staircase method was used to determine each participant's estimated threshold speed for each unloading environment. Results showed that participants' estimated threshold speed was lower than the visual speed in every condition. This phenomenon has been observed previously when combining treadmill walking with virtual reality (Banton et al. 2005; Caramenti et al. 2018), however, this study demonstrated that this effect persists in an unloaded environment.

There were no statistically significant differences in estimated threshold speeds between the three conditions. However, this may be due to the averaging of the participants, many of whom had individual responses to the various unloading conditions ($n = 8$ increased speed, $n = 5$ decreased speed), and some who had no reaction ($n = 4$). These differing responses to the task may be due to biomechanical differences, as participants are free to behave differently as the load and speed of the treadmill are manipulated (Goldberg and Stanhope 2013). Participant biomechanics may also differ through the personal preference of placement of the arms/hands on the AlterG treadmill. Varying interactions between the shoulders and hips may arise as participants may modify their walking stance due to the AlterG cockpit being placed around their hips. And finally, participants may have had varying knee and ankle flexion due to the various unloading conditions with some participants observationally lacking a heel strike in their gait in the 20% condition and others continuing to heel strike despite the unloading. This alteration has been demonstrated in previous research using a lower body positive pressure treadmill, which found that at < 80% body weight settings there was a significant shift to forefoot loading (Smoliga et al. 2015). Additionally, previous research has shown that people have more precision in their estimation of self-motion when they have both visual and vestibular cues readily available (Gu et al. 2008; Angelaki et al. 2011). However, optic flow in VR has been shown to affect the sensitivity to vestibular signals due to a reduced weighting of vestibular cues, leading to changes in perception of self-motion (Gallagher et al. 2020).

Individualized responses to various forms of sensory stimulation have been previously demonstrated. For instance, in the study of postural control, interindividual differences can result from subjects adopting different frames of references to complete a motor control task (Isableu et al. 2010). Individual responses also occur in response to visual stimulation which may be due to differences in visual imagery vividness and precision which affects perception (Reeder 2017; Salge et al. 2021). Similarly, individual differences are also found after attempting to train subjects to increase their performance on an auditory selective attention task (Laffere et al. 2020). There are also large individual differences in susceptibility to motion sickness which may be due to a combination of demographic, physiological, and psychological factors (Mittelstaedt 2020; Stelling et al. 2021). And finally, astronauts returning from microgravity adopt different strategies to head and trunk movement latency, with responders being categorized into 'increaser' and 'decreaser' groups (Madansingh and Bloomberg 2015). These studies show that different humans display different response patterns to changing sensory environments, particularly ones that they have relatively little experience with. Additionally, the one subject who did not respond in the same direction across conditions had only a minimal change (0.1 mph). This further reinforces the notion that the overall trend aligns with a consistent pattern of change.

Motion sickness while using VR, also known as "cybersickness", can occur when a user is primarily stationary but experiences a sense of motion in the visual environment (LaViola 2000; Lohman and Turchet 2022). This can lead to symptoms such as nausea, sweating, dizziness, and headaches depending on individual susceptibility (Chung and Barnett-Cowan 2023) and may be due to gender differences (Aldaba and Moussavi 2020). Such symptoms would likely prevent a user from using this technology, especially in an exercise setting. In this study, none of the participants reported any symptoms of cybersickness, which may be due to participants walking on the treadmill at speeds they perceive to be equivalent to the visual speed. When the speeds are no longer equivalent (reversal points), participants only spent 15 s at that “mismatched” speed before returning to a speed within their acceptable range. Cybersickness may have also been prevented by using a VR HMD that had a high screen resolution and fast refresh rate as previous studies combining VR and treadmill walking have demonstrated these factors may contribute to cybersickness (Calogiuri et al. 2018; Saredakis et al. 2020). Additionally, since the visual scene speed remained constant, it was predictable, which has been shown to be less likely to provoke motion sickness compared to unpredictable motion (Kuiper et al. 2020).

Despite the mixed results, this study helps to inform the design and use of VR with a treadmill. App designers may consider having new users complete a tutorial that tests their speed perception and establish an estimated threshold speed based on a walking and/or running speed. The difference between these individual estimated threshold speeds and the visual speeds could be used to customize the user experience and prevent motion sickness symptoms. Additionally, 17 out of 18 participants reported this being their first experience using a VR HMD, and all participants communicated that they had a positive and enjoyable experience after completing the protocol. This ease of use and enjoyability of using virtual reality while exercising has been widely demonstrated with higher immersion leading to increased motivation and engagement (Neumann and Moffitt 2018; Mouatt et al. 2020; Winter et al. 2021). Combining virtual reality with exercise also promotes adherence to training protocols (Annesi and Mazas 1997; Davis et al. 2022), which may be due to users having an improved performance due to a lower level of perceived exertion (Mestre et al. 2011; Glen et al. 2017; Barathi et al. 2018; Farrow et al. 2019).

5 Conclusions

In this study, despite variations in the direction of change in estimated threshold speed in response to various unloading conditions, the magnitude of change remained relatively the same, demonstrating that subjects changed in a consistent way. Some experienced a positive change in estimated threshold speed, while others had a negative change, which can be attributed to their individual preferences or strategies. It is also worth noting that the absolute magnitude of response was not significantly impacted by the amount of load, regardless of the direction of change. Additionally, the one subject who did not respond in the same direction across conditions had only a minimal change (0.1 mph). This further reinforces the notion that the overall trend aligns with a consistent pattern of change. Most notably, this study demonstrated that the underestimation of walking speed compared to the visual scene speed is exaggerated during unloaded treadmill walking.

These findings have implications for the design of a workout regimen for moon-based astronauts, spaceflight participants, or space tourists. It is important to prevent these populations from becoming motion sick while exercising so they can complete the full duration of a prescribed workout. It will also ensure full immersion in the virtual environment by feeling as realistic as possible, therefore increasing the likelihood of compliance with using an HMD. These results also contribute to the current literature as this combination of an unloading treadmill and VR HMD hasn’t been studied before as it relates to speed perception.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10055-024-01077-x.

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Author contributions H.G. and C.L. designed the study and analyzed the results. H.G. carried out the experiments, performed statistical calculations, and wrote the manuscript with input from C.L.

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Data availability The datasets generated and evaluated during the current study are available from the corresponding author on request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval All participants gave their informed and written consent prior to their inclusion in the study, which was performed in accordance with the ethical standards specified by the 1964 Declaration of Helsinki and approved by the Institutional Review Board of the University of Houston (STUDY00003754).

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