Evaluation of Drone-Induced Balance Loss of Roofers on Sloped Surfaces

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ABSTRACT

Roofers face high risks of injuries and fatalities while working on inclined surfaces with awkward postures. The presence of drones may exacerbate these risks by distracting workers and impairing their postural stability. This study evaluated the effects of drone distraction on roofers' postural stability. Twenty-two participants simulated shingle installation on a wooden roof platform with three roof pitches (0, 3/12, 6/12) and four drone conditions (no drone and drones at 16, 48, and 82 ft). Using a virtual reality (VR) headset, participants experienced a virtual roof site while kneeling on a force plate. Center of pressure (COP) trajectories were recorded and processed into a stability indicator of sway area for statistical analysis. Results showed that closer drone proximity significantly increased distraction, compromising stability. These findings emphasize the need to address drone-induced safety challenges in roofing environments to protect roofers' safety.

INTRODUCTION

Roofing is among the most hazardous construction sectors and falls from roofs comprise one of the leading causes for work-related fatalities (Choi 2008). Roofers have one of the highest rates of injuries and illnesses of all occupations, as well as one of the highest rates of occupational fatalities (Bureau of Labor Statistics 2024). In environments that are challenging to the postural control system, individuals face heightened risk of losing their balance which could lead to a fall (Sun et al. 1996). Research has revealed that roof work environment contributes to an individual's increased risk of loss of balance as roofing work requires precise control of roofers to maintain posture while minimizing balance disturbances (Simeonov et al. 2003). Inclined surfaces (roof) have a detrimental effect on postural stability (Wade and Davis 2009). Given these challenges, the introduction of external distractions, such as drones, may further exacerbate the risks of loss of balance for roofers working on elevated and inclined surfaces.

In recent years, the use of drones in the construction industry has grown significantly, and in 2023 the global construction drone market size was valued at $6.5 billion and is projected to reach $19 billion by 2032 (Chinchane and Mutreja 2024; Hatoum and Nassereddine 2022). Some of the areas of drone use in the construction industry consist of survey mapping, inspection, job material tracking, project progress monitoring and damage detection (Sanson 2019; Yildiz et al. 2021). Drones are expected to have many advantages, but in recent years, there has been a growing concern that their use could pose additional safety risks and hazards at construction sites (Tatum and Liu 2017). Research has supported the idea of a drone being one of the primary sources of distraction in the workplace (McCabe et al. 2017). Workers' bodily responses in hazardous areas exhibit greater irregularity compared to nonhazardous areas (Kim et al. 2017). Postural instability presents a safety risk for workers, particularly in industries such as construction (Chander et al. 2017). Because of the high level of risk and unpredictable working conditions, roofers need to be more alert and focused. Roofers at heights, who already have the greatest fatality rates, are particularly vulnerable to these additional risks introduced by drones (Albeaino et al. 2023; Jeelani and Gheisari 2021). While many studies have explored drone-induced risks for construction workers, very few, if any, focus specifically on roofers. The objective of this study is to evaluate how drone-induced distractions affect roofers' balance on sloped surfaces.

BACKGROUND

Severity of drone-induced hazards in construction workplaces

With the predicted rise in construction works to meet the growing infrastructure needs of the United States, with the rapid increase in the use of drones for construction activities, there will likely be more interaction between human workers and autonomous machines such as drones. Drone generated safety risks include collision with humans and property, privacy invasion, visibility obstruction, system malfunction, loss of control, and distraction (Hu et al. 2024; Tatum and Liu 2017).

The introduction of drones can have significant consequences as drones flying over or near workers might cause distractions (Albeaino et al. 2023). A drone intruding into an individual’s personal zone, which typically varies between 0 ~ 3.05 m, may cause distraction, stress and discomfort (Izadi Moud et al. 2021). The breach of this proximity may become more dangerous as the unpredictable nature of construction makes workers’ activities more complex and challenging, demanding more cognitive skills in terms of attention, vigilance, physical strength, and reflex. Drones are reported to have the ability to draw attention by disrupting the worker's concentration from their work (Li and Liu 2019; Martinez et al. 2020). Additionally, drones can have psychological impacts, such as a perceived invasion of privacy or the discomfort of feeling watched. These safety concerns can lead to accidents like loss of balance and subsequent falls, which are particularly critical for roofers working at heights. (Hu et al. 2024).

Most of the previous studies on the risks and hazards associated with drone use in construction mainly relied on surveys, expert opinions, and conceptual analyses. These studies mainly focused on the physiological, emotional and attentional impacts induced by human-drone interaction. However, there is a lack of quantitative analysis on how drone induced distractions affect postural stability, which is particularly critical for roofers working on inclined surfaces, where maintaining balance is challenging and the risk of falls is significantly higher.

VR assisted research in drone-induced distraction

Immersive technologies, such as VR, are gaining popularity in construction, particularly for studying safety-related scenarios (Elghaish et al. 2021; Wang et al. 2018). An immersive virtual environment offers an excellent opportunity to study safety challenges in construction workers by providing a risk-free setting where participants can experience hazardous situations without facing any adverse consequences. For instance, VR has been utilized for training construction workers on drone safety, proving to be more effective than conventional techniques at enhancing performance and knowledge retention (Jeelani et al. 2020; Szóstak et al. 2024). A VR-based safety course offers a safe environment for workers to practice tasks and enhance their skills without the risk of real-life dangers (Zhao and Lucas 2015). Psychophysiological or emotional effects of drones on workers have also been evaluated using VR and results showed that drone presence was not associated with changes in participants' physiological and emotional states but that participants diverted some of their attention from the assigned task toward the drone (Albeaino et al. 2023; Jeelani and Gheisari 2021). Many studies have explored how drones distract participants' attention from their tasks, but these studies did not evaluate how drone-induced distraction impacts the balance of roofers working on sloped surfaces, where such imbalance could result in falls or injuries.

METHODS

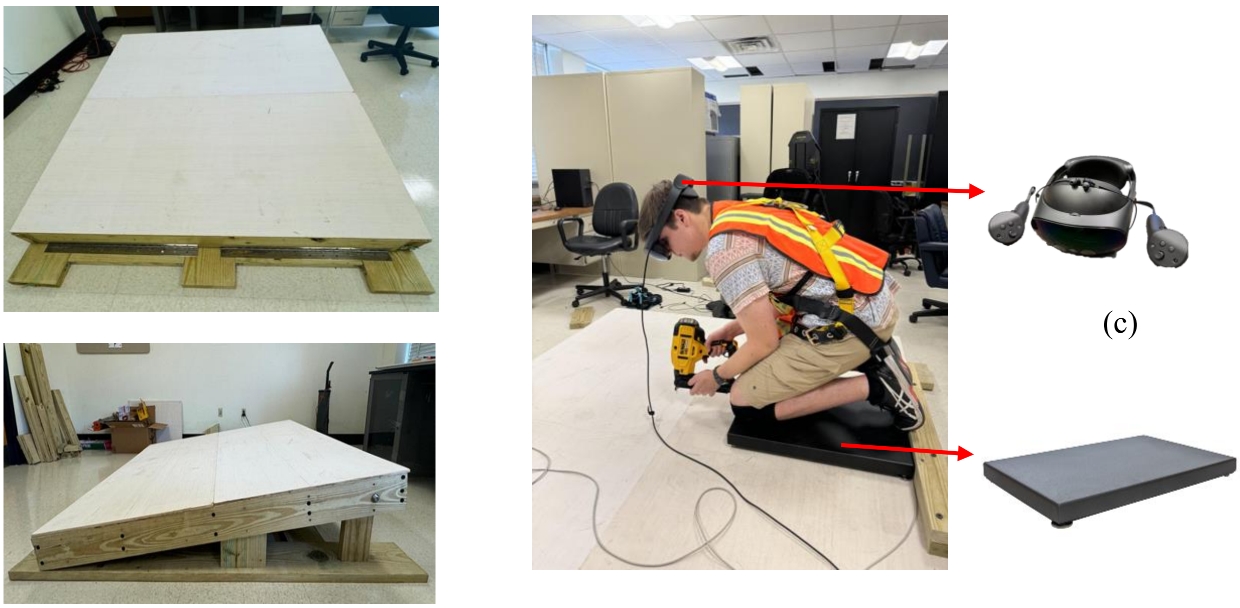
Participants. A total of 22 volunteers (12 male and 10 female) participated in this experiment. The protocol was approved by Institutional Review Board (IRB) of West Virginia University (WVU).

Variables. The experimental design was comprised of two independent variables: roof slope and drone intrusion height. The roof slope included three levels: 0°, 3/12 pitch, and 6/12 pitch and drone intrusion as no drone, drone at 16ft, 48ft and 82 ft. A study examined the effectiveness of using drones for visual inspections and determined that clear images can be captured when the drone is positioned between 16 and 82 feet in height (Morgenthal and Hallermann 2014). Based on these findings, 16 ft, 48 ft, and 82 ft drone height from the roof surface was selected in this experiment. The roof slopes were chosen to represent the typical roof pitches found on construction sites (Johnson 1976). The control variable was the drone flying direction, which moved front-to-back and back-to-front relative to the participant, aligning with the anteroposterior direction (the direction the participant was facing the slope).

The dependent variable was 95% confidence ellipse area, also known as the sway area, which was calculated from the force plate data to assess the postural balance stability. This metric has been widely employed in previous studies to assess postural stability (Bendo et al. 2013; Merlo et al. 2012; Prieto et al. 1996; Schubert et al. 2014). A larger sway area typically indicates greater body sway and less stability, suggesting that the individual is struggling to maintain balance. In contrast, a smaller sway area reflects better balance and postural control.

Instruments. Simulated nailing shingles on rooftop was conducted on a custom-build adjustable wooden platform measuring 6ft × 6ft which mimicked a residential rooftop (Figure 1a). The platform's slope was adjustable using two sets of wooden legs, allowing for slope settings of 0°, 3/12 pitch and 6/12 pitch. For high-pitched slopes, a wooden plank was attached to the platform to provide additional foot support for participants. Ground reaction forces were collected using a force plate (Bertec FP5060D-06-PT-2000) which was placed on the roof platform (Figure 1d).

A Meta Quest Pro VR headset (Figure 1c) was used to immerse participants in a virtual environment. Figure 1b illustrates the setup, showing a participant mimicking nailing shingles on rooftop. The virtual environment was created using Unity software, where three distinct virtual roof scenes were created to represent different roof pitches. Figure 2 shows a sample virtual roof scene which was created in Unity. These roof scenes were designed to simulate realistic roofing conditions and tasks.



(a) (b) (d)

Figure 1. (a) Wooden platform, (b) Participant mimicking nailing shingles, (c) VR headset, (d) Force plate

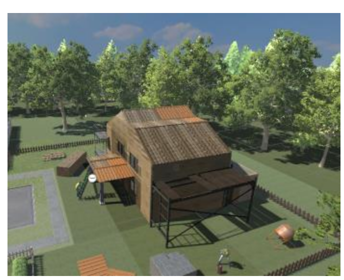


Figure 2. Virtual roof scene

Procedures. Upon arrival, participants were introduced to the experiment procedure and then they were given brief training with the VR headset in the kneeling posture on the force plate to adjust to the virtual scene. Additionally, before collecting data the VR headset was calibrated to ensure proper alignment of the virtual scene with the roof platform. Then the participants read and signed the informed consent forms. After that, participants were asked to wear a high-visibility vest and a fall protection harness to simulate a realistic working environment. To ensure comfort during kneeling tasks, participants were also provided with knee pads. Then they mimicked nailing shingles task in kneeling posture on a force plate positioned on a wooden roof platform while wearing VR headset that immersed them in a virtual roof scene. Three virtual roof scenes were created to correspond to the three different roof pitches, and each virtual scene was aligned with the roof platform for every trial.

The force plate was aligned on the platform such that the anteroposterior (AP) direction (y-axis) representing forward-backward movements aligned with the participant's facing direction, while the mediolateral (ML) direction (x-axis) captured side-to-side movements of the participants. A virtual drone was programmed to take off and hover over the front and back of the participant. Participants were instructed to maintain their kneeling posture as much as possible but were allowed to react naturally to any distractions caused by the drone's visual or auditory presence. Trials were conducted on the roof simulator across three slope pitches and four drone conditions, resulting in 12 (3 × 4) total scenarios. To control order or sequence effect, the 12 scenarios were randomized by slope and then drone flying heights for each participant, with each participant experiencing all the scenarios once during the experiment. Each trial lasted 30 seconds and the force plate recorded data at 100 Hz.

DATA PROCESSING

Although each trial lasted 30 seconds, the initial 5 seconds and final 2 seconds of data were excluded from analysis to avoid the effects of initial transients and anticipation. Since the drone was visible in the virtual scene from 8 seconds to 26 seconds, this time frame was used for analysis to ensure the focus remained on the participants' reactions to the drone's presence.

To account for the variability in knee and foot positions on the force plate, we centered the COP trajectories relative to their arithmetic mean in our analysis, consistent with the approach used in most previous studies (Prieto et al. 1996; Qiu and Xiong 2015). Then the force plate data were used to evaluate the sway of COP in ML and AP directions, denoted as COP_x and COP_Y, respectively. The 95% confidence ellipse area (sway area) was used to measure postural balance stability.

DATA ANALYSIS

Two-way, 3 (slope) × 4 (drone intrusion) repeated measures analysis of variance (ANOVA) was used to evaluate the effects of the two independent variables and their interaction on the dependent variable. To improve the normality of residuals, the model was fitted to the natural logarithm of sway area. Levene's test was conducted to assess the homogeneity of variances, and the assumption was satisfied. Mauchly's Test of Sphericity was applied to evaluate the sphericity of the data. If the test confirmed sphericity, no correction was necessary. However, when sphericity was violated, the Greenhouse-Geisser correction was applied if epsilon was below 0.75, while the Huynh-Feldt correction was used if epsilon exceeded 0.75. Post hoc pairwise comparisons were performed to identify specific differences between conditions. The data analysis was carried out using SPSS v29 (IBM Corp. Armonk, NY) and levels of significance (*p* value) were set to 0.05.

RESULTS

Table 1 shows the results of statistical analysis, and the findings reveal that both drone intrusion and slope have significant individual effects on balance (measured as log sway area). Additionally, significant interaction between slope and drone intrusion is also present.

Table 1. Results of Repeated Measure ANOVA

Independent Variables	P – value
Drone-Intrusion	<.0001
Slope	0.029
Drone-Intrusion*Slope	0.042

Effect of drone-intrusion. Table 2 shows the result of pairwise comparisons between drone-intrusion conditions by post hoc test. Pairwise comparisons showed significant differences in sway area between the 'no-drone' condition and all drone heights. Additionally, there was a significant difference between 16ft and 82ft. The sway area is significantly smaller in the 'no drone' condition (0.429 ± 0.074) compared to all other drone conditions. The highest sway area was observed when the drone was at 16 ft (0.911 ± 0.121), followed by the drone at 48 ft (0.750 ± 0.132) and 82 ft (0.700 ± 0.111). Additionally, the sway area was significantly larger when the drone was at 16 ft compared to 82 ft. These results suggest that participants were more distracted by the drone when it was closer, either due to visual or auditory distractions.

Table 2. Pairwise comparison between drone-intrusion conditions

Drone-intrusion conditions	Significant difference
No drone – 16ft	**
No drone – 48ft	**
No drone – 82ft	**
16ft – 48ft	
16ft – 82ft	**
48ft – 82ft	

**indicates statistical significance ($p < 0.05$)

Effect of slope. Table 3 shows the result of pairwise comparisons by post hoc test to determine significant differences between roof slope groups. Pairwise comparisons revealed that sway area significantly differed between 0° and 6/12 pitch, as well as between 3/12 pitch and 6/12 pitch. No significant difference was observed between 0° and 3/12 pitch. The sway area was significantly lower on the 6/12 pitch roof (0.358 ± 0.082) compared to both the 0° slope (0.520 ± 0.053) and the 3/12 pitch (0.493 ± 0.076) indicating greater instability on the flatter surfaces.

Table 3. Pairwise comparison between slopes

Slope	Significant difference
0° – 3/12 pitch	
0° – 6/12 pitch	**
3/12 pitch – 6/12 pitch	**

**indicates statistical significance ($p < 0.05$)

Interaction effect of drone intrusion and slope. In Table 1 significant interaction between slope and drone-intrusion were noted. Results revealed that sway area was significantly lower in the 'no drone' condition (6/12 pitch: 0.296 ± 0.063, 3/12 pitch: 0.386 ± 0.091, 0° slope: 0.272 ±

0.069) compared to all drone intrusion conditions across all roof slopes. Sway area was highest when the drone was at 16 ft across all slopes (6/12 pitch: 0.685 ± 0.076, 3/12 pitch: 0.620 ± 0.093, 0-degree slope: 0.457 ± 0.119), followed by the 48 ft and 82 ft drone heights.

DISCUSSION

In this study, the authors determined and documented how the inclusion of drones in the roofing sites can impact the roofers balance during kneeling on different sloped surfaces. To assess the impact of drone distraction on roofers' balance during the shingle installation in kneeling posture, two factors—roof slope and drone intrusion were examined.

Findings highlighted that the addition of the drones in the virtual roofing scenes significantly affected the participants' balance. The sway area was greatest when the drone was at a height of 16ft, followed by 48ft and 82ft, and was lowest in the absence of a drone. These results indicate that drone proximity significantly impacts balance, with greater distraction occurring when the drone is closer. This may happen because the closer the drone flew overhead, the more prominent the noise and visual presence, amplifying the distraction. This finding is consistent with previous studies that underscored the risks associated with drone-induced distractions.

Additionally, roof slope significantly impacted balance. The sway area was smaller on the 6/12 pitch roof compared to both the 0° slope and the 3/12 pitch, suggesting that balance control was greater on the steeper surfaces. These results are consistent with previous studies (Chen et al. 2021). This suggests that participants were more relaxed and less focused on balance control on lower or flatter surfaces compared to elevated or steeper surfaces. On steeper slopes, participants may have been more cautious and actively engaged in greater effort to maintain stability, resulting in reduced sway.

These results suggest that both roof slope and drone distractions can compromise roofers' stability. Although the impact of slope in real roofing environments may be difficult to control, it is crucial to understand how drones affect roofers' postural stability, as such distractions can increase the risk of falls or injuries. This underscores the need for further research into mitigating these risks through design interventions or safety protocols.

CONCLUSIONS AND FUTURE WORK

This study employed VR technology to study postural stability of roofers working at different distances from drones on sloped surfaces. The findings showed that roof slope, drone intrusion and their interaction all have an association with the postural stability of roofers. Drones significantly distract roofers and reduce their attention on the task at hand. Moreover, the results suggest that drones flying in close proximity cause more distraction than drones flying at greater distance, leading to difficulties in maintaining their balance. By identifying the impact of drone proximity on balance, the findings provide valuable insights for improving safety guidelines and integrating drones more effectively into roofing operations. To mitigate drone-induced distractions, roofing sites could establish minimum flyover distances or restrict drone operations during high-risk tasks. The knowledge generated through this study will not only help in better understanding safe drone integration in roofing worksites but could also contribute to the development of comprehensive regulations for drone usage in this industry.

The future extension of this study will include to address the following limitations. Firstly, the current VR environment lacks certain physical elements including wind disturbances and variations in rotor noise, which could influence workers' reactions. Secondly, this study assessed postural balance based only on sway area, without using other balance metrics that could provide additional understanding. Lastly, only kneeing posture was investigated in this study while roofers adopt various postures during shingle installation.

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