Assessing Impacts of Drone-Induced Distraction on Postural Stability of Roofers during Shingle Installation on Inclined Surfaces

Mahfuza Maisha Mouri, S.M.ASCE[1]; Wei Han[2]; Liqun Xu, S.M.ASCE[3]; Alireza Ghasemi, S.M.ASCE[4]; Wei-Yin Loh, Ph.D.[5]; Zhenhua Zhu, Ph.D., A.M.ASCE[6]; and Fei Dai, Ph.D., M.ASCE[7]

Abstract: Roofers face elevated injury risks due to the hazardous nature of working on inclined surfaces, which often require awkward postures and precise balance. The increasing use of drones in construction introduces a potential new hazard, because their presence may distract roofers and impair postural stability. Although prior studies have explored the impact of drones on workers' attention, there is limited research on their effects on workers' balance, particularly in high-risk environments such as roofing. This study investigated the effects of drone distraction on roofers' balance on the slanted roof surface. A controlled laboratory experiment was conducted with 24 participants who simulated a static shingle installation task on an adjustable wooden platform while wearing a virtual reality (VR) headset. The VR environment replicated three roofing conditions (i.e., pitch slopes 0, 3/12, and 6/12), under four drone conditions [i.e., no-drone control, and drone intrusions at altitudes of 4.88 m (16 ft), 14.63 m (48 ft), and 24.99 m (82 ft)]. Center of pressure (COP) data were recorded using a force plate and then processed into metrics, including mediolateral (ML) and anteroposterior (AP) maximum COP displacement, ML and AP RMS displacement, and sway area, to assess balance stability. The results demonstrated that closer drone proximity significantly increased distraction, leading to greater postural instability. These findings highlight the potential safety risks posed by drone operations near roofing work and underscore the need for guidelines on safe drone deployment in construction zones to minimize worker distraction and enhance fall prevention strategies. **DOI: 10.1061/JCEMD4.COENG-17685**.

Author keywords: Roofers; Postural stability; Center of pressure; Kneeling; Inclined surfaces; Drones; Virtual reality.

Introduction

Roofers have one of the highest rates of injuries, illnesses, and occupational fatalities across all professions (Bureau of Labor Statistics 2024). They are about 6 times more likely to experience fatal occupational injuries than the average construction workers, and falls from roofs account for 75% of these fatalities (Ruser 1995). Fatality investigation reports and workers' compensation records frequently cite slips, trips, and loss of balance as primary causes of roofing falls (Hsiao and Simeonov 2001). Working on steep, inclined, and often slippery surfaces demands precise balance control to prevent falls and maintain stability (Fredericks et al. 2005). Such roofing conditions significantly increase the risk of balance loss, because roofers must constantly adjust their posture while minimizing disturbances to stability (Simeonov et al. 2003). Steep roof pitches are particularly hazardous, and studies show that inclined surfaces heighten slip risk and negatively affect postural stability (Parsons and Pizatella 1984; Wade and Davis 2009). Additionally, handling heavy materials, operating equipment on confined surfaces, and working on temporary or incomplete surfaces require workers' careful attention, which makes the control of balance challenging (Fredericks et al. 2005). Shingle installation, which is a common task performed by roofers on the jobsite, is a prolonged, repetitive, and awkward task that increases the physical demands placed on roofers in residential construction. Because these factors often are unavoidable, reducing safety risks of roofers remains a challenging task.

In recent years, drones, also known as uncrewed aerial vehicles (UAVs), have become increasingly popular in the construction industry due to their observable benefits (Yildiz et al. 2021; Zhu et al. 2023). In 2017, there was a 239% increase in drone utilization in the construction sector, which exceeded the growth in any other commercial industry (Yildiz et al. 2021). Drones are being utilized increasingly for a wide range of applications in construction, including survey mapping (Adjidjonu and Burgett 2021; Costa and Mendes 2016), data collection and inspection tasks (Eiris et al. 2021; Rakha and Gorodetsky 2018), project progress monitoring (Martinez et al. 2020; Unger et al. 2014),

[1]Graduate Research Assistant, Wadsworth Dept. of Civil and Environmental Engineering, West Virginia Univ., Morgantown, WV 26506. Email: mm00286@mix.wvu.edu

[2]Graduate Research Assistant, Dept. of Civil and Environmental Engineering, Univ. of Wisconsin–Madison, Madison, WI 53706. Email: whan59@wisc.edu

[3]Graduate Research Assistant, Dept. of Civil and Environmental Engineering, Univ. of Wisconsin–Madison, Madison, WI 53706. ORCID: https://orcid.org/0000-0001-5214-5592. Email: liqun.xu@wisc.edu

[4]Graduate Research Assistant, Wadsworth Dept. of Civil and Environmental Engineering, West Virginia Univ., Morgantown, WV 26506. ORCID: https://orcid.org/0000-0003-4745-8169. Email: alireza.ghasemi@mail.wvu.edu

[5]Professor, Dept. of Statistics, Univ. of Wisconsin–Madison, Madison, WI 53706. Email: loh@stat.wisc.edu

[6]Assistant Professor, Dept. of Civil and Environmental Engineering, Univ. of Wisconsin–Madison, Madison, WI 53706. Email: zzhu286@wisc.edu

[7]Professor, Wadsworth Dept. of Civil and Environmental Engineering, West Virginia Univ., Morgantown, WV 26506 (corresponding author). ORCID: https://orcid.org/0000-0002-8868-2821. Email: Fei.Dai@mail.wvu.edu

Note. This manuscript was submitted on June 4, 2025; approved on November 4, 2025; published online on March 27, 2026. Discussion period open until August 27, 2026; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364.

damage detection (Calantropio 2019), and safety inspection (Zhou and Gheisari 2018). This rapid growth of drone utilization on construction jobsites is expected to persist in the coming years. In 2023, the global construction drone market was valued at $6.5 billion, and it is expected to grow significantly, reaching $19 billion by 2032 (Chinchane and Mutreja 2024).

Despite the benefits offered by the use of drones, there has been growing concern about their potential to introduce additional safety risks and hazards on construction sites (Karakhan and Al-Mhdawi 2024; Tatum and Liu 2017). Drones are one of the primary sources of distraction in the workplace (McCabe et al. 2017). As drone integration in construction continues to expand, their safety challenges may further increase the risks on job sites, particularly for workers operating in hazardous conditions (Zhu et al. 2023). Given the high-risk nature and unpredictable conditions of roofing work, roofers already have the highest fatality rate, and they are particularly vulnerable to the additional risks posed by drones (Albeaino et al. 2023). Although much research has examined the risks that drones present to construction workers in general, limited attention has been given to roofers, a group that faces unique challenges due to the nature of their work. Roofers operate at height, often on sloped surfaces, which already presents a heightened risk for falls and other accidents. The addition of drones into this environment could introduce further complications, such as distraction and loss of balance.

Literature Review

Safety Risks Associated with Drones in Construction Workplaces

Drone-induced safety risks include direct impact from falling drones debris (Opfer and Shields 2014), concerns over privacy invasion due to constant surveillance (Finn and Wright 2012), loss of control, and potential distractions on job sites (Moud et al. 2019). Izadi Moud et al. (2021) found that when a drone enters an individual's personal space, typically ranging from 0 to 3.05 m, it can lead to distraction, stress, and discomfort. The noise and movement produced by drones can contribute further to worker distraction and diminished concentration (Moud et al. 2019). Effective hazard recognition, which is essential for identifying potential risks, requires a high degree of focus and awareness (Fleming and Fischer 2017). Distractions interfere with key cognitive functions such as perception, reasoning, attention, and situational awareness, increasing the risk of accidents (Khalid et al. 2021). The unpredictable nature of construction work increases its complexity and challenges, requiring workers to engage more in cognitive skills, including vigilance, attention, physical strength, and reflexes. Drones have been reported to disrupt worker concentration by drawing attention away from tasks (Li and Liu 2019; Martinez et al. 2020). Moreover, drones can have psychological effects, such as creating a sense of privacy invasion or discomfort from feeling observed, which can be stressful for workers and may result in poor performance and unsafe behavior (Zhu et al. 2023). These safety concerns may lead to incidents such as loss of balance and subsequent falls, posing significant risks, especially for roofers working at heights (Hu et al. 2025).

Although previous studies have examined the safety concerns of drone integration in construction, there remains a significant gap in understanding their direct biomechanical effects on roofers. Much of the existing research on drone-related risks relies on surveys, expert opinions, and conceptual analyses, primarily addressing the physiological, emotional, and attentional impacts of human–drone interaction. Although the literature acknowledges that drones can disrupt worker concentration and induce psychological stress, few studies have empirically measured how these distractions affect postural stability. This gap is particularly concerning for roofers working on inclined surfaces, on which maintaining balance is inherently challenging, and the risk of falls is substantially higher.

Virtual Reality–Assisted Research in Drone-Induced Distraction

Virtual reality (VR) is a computer-generated simulation of a three-dimensional (3D) environment that allows users to interact in a seemingly real or physical way using specialized digital systems, such as head-mounted displays or sensor-equipped gloves (Whyte 2003). An immersive virtual environment is a valuable tool for studying safety challenges in construction. Workers can experience hazardous situations in a risk-free setting, without any real-world danger. This is why VR is becoming increasingly popular in the construction industry, especially for examining safety-related scenarios (Wang et al. 2018). Studies have used VR to simulate high elevations, and results showed no significant differences in height effects on human stance between VR and real environments, supporting the use of VR in studying human behavior at elevations (Cleworth et al. 2012). Several studies have explored the use of VR-based environments for training and assessing safety performance in construction. For example, VR has been used to train construction workers on drone safety, and it has proven to be more effective than traditional methods in enhancing performance and knowledge retention (Szóstak et al. 2024). A 360° VR training environment was developed to educate construction workers about drone safety challenges and countermeasures. The repeated measures study design showed that the 360° VR training significantly improved users' safety knowledge about drones (Cheng et al. 2023). Additionally, a VR safety training environment was designed to teach construction workers how to safely interact with drones on job sites, addressing both current and future drone-mediated applications through a detailed design and development process (Albeaino et al. 2022). Psychophysiological or attentional effect of drones on workers at heights also has been evaluated by creating VR environment. The results indicated that UAVs cause distraction and reduce workers' attention to the tasks at hand (Albeaino et al. 2023; Jeelani and Gheisari 2022).

Recent studies have increasingly employed VR to examine the impact of drones on construction workers, particularly in safety training and cognitive assessments. Researchers also have investigated the emotional and psychophysiological effects of drones in VR environments, and found that drone presence can cause distractions and impair task focus. These studies offer valuable insights into drone-related risks and demonstrate the potential of VR to assess safety concerns without exposing participants to real-world danger. However, they mainly focus on cognitive and perceptual factors rather than on the direct biomechanical effects of drone-induced distractions.

Problem Statement and Research Objective

Based on the review, there is a lack of empirical research examining how both visual and auditory drone presence directly impact roofers' biomechanical stability. Roofers face heightened risks due to the challenges of maintaining balance on inclined surfaces, and the presence of drones could further compromise their stability, increasing the likelihood of falls and accidents. The objective of this study was to empirically investigate the impact of drone presence at varying distances on roofers' postural balance with the assistance of VR, thereby extending previous conceptual- and survey-based research. The findings will contribute to the development of safety guidelines for drone-integrated construction environments and thereby enhance roofers' safety on construction sites.

Methods

Participants

A total of 24 healthy volunteers (15 male, and 9 female) participated in this experiment. All participants were young adults and physically active. Although these participants were not actual roofers, they had relevant internship or employment experience for the construction industry. The study protocol was approved by the Institutional Review Board (IRB) of West Virginia University (WVU).

Variables

There were three types of variables in this study: control variables, independent variables, and dependent variables.

Control Variables

Control variables—drone flying speed, sound and flight direction—were kept constant. The drone speed typically is fixed for visual data capture when drones are used for monitoring and inspection tasks (Zhu et al. 2022). For example, a drone speed of 11 mph (5 m/s) was set to optimize 3D flight templates and develop an algorithm that maximized visual quality while minimizing flight execution duration (Ibrahim and Golparvar-Fard 2019). A flight speed of 2–6 m/s was used to assess the safety risk of drones on construction sites through four-dimensional (4D) simulation (Zhu et al. 2022). In the present study, a fixed drone flight speed of 11.2 mph (~5 m/s) was selected. Drone flying sounds were sourced from a recorded soundtrack of an actual drone to simulate realistic drone integration scenarios. The drone's flying direction was front-to-back and back-to-front relative to the participant, aligning with the anteroposterior direction (the direction in which the participant was facing the slope).

Independent Variables

The experimental design comprised two independent variables: roof slope and drone intrusion. The roof slope included three levels (0°, 3/12 pitch, and 6/12 pitch), and no drone intrusion and drone heights of 4.88 m (16 ft), 14.63 m (48 ft), and 24.99 m (82 ft). These roof pitches were chosen based on common roof pitches found on construction sites (Johnson 1976). In this study, drone height is defined as the distance from the drone to the roof's surface or boundary. A study of the application of drones for visual inspection and damage detection of structures found that, under favorable environmental conditions, detailed images generally could be captured from distances ranging between 5 m (16.40 ft) and 25 m (82.02 ft) to provide comprehensive structural information (Morgenthal and Hallermann 2014). The drone's distance from the building surface can range from 16 to 82 ft, so in simulation scenarios the virtual drone's altitude should be the building's height plus an additional 16–82 ft (Zhu et al. 2022). Therefore, in this experiment, drone heights of 16, 48, and 82 ft were selected.

Dependent Variables

The dependent variables used to assess postural balance stability included sway area, maximum distance in the mediolateral (ML) and anteroposterior (AP) directions, and RMS in the ML and AP directions.

Maximum displacement in the ML or AP direction reflects the largest excursion of the center of pressure (COP) in that direction. An increase suggests reduced ability to sustain balance. Even a small perturbation, such as a sudden noise, can cause a larger than normal displacement (Palmieri et al. 2002). This metric was used to capture whether drone distractions led to sudden and extreme weight shifts, which may increase the risk of falls for roofers. RMS measures the average absolute displacement of the COP in the ML or AP direction, and reflects variability in postural changes over time (Palmieri et al. 2002). An increased value suggests a decreased ability to maintain postural control (Geurts et al. 1993). RMS values in both directions were used to indicate whether participants required more-frequent or -pronounced corrective movements in each direction due to distractions in order to maintain balance. Sway area represents the total area covered by the COP trajectory. Larger values generally reflect greater difficulty maintaining posture, and have been associated with higher fall risk (Merlo et al. 2012). These metrics capture distinct but complementary aspects of postural stability. Considering them together provides a comprehensive assessment of balance, whereas examining each individually allows insight into specific mechanisms of postural control under distraction.

Instruments

To replicate a residential roof an adjustable, custom-built wooden roof platform was constructed measuring 1.83 × 1.83 m (6 × 6 ft) [Fig. 1(a)]. Two sets of wooden legs were bolted next to each other to set the platform at two different slopes (3/12 and 6/12 pitch). For steeper slopes, a wooden plank was added to the platform to offer extra foot support for participants. Ground reaction forces were measured using a force plate (Bertec FP5060D-06-PT-2000, Columbus, Ohio) [Fig. 1(d)] with a sampling rate of 100 Hz. The force plate was connected via a USB port to a computer running Bertec Digital Acquire 4.3.1 software. Participants wore a Meta (Menlo Park, California) Quest Pro headset [Figs. 1(b and c)] and mimicked a shingle installation task while holding a nail gun on the force plate which was positioned on the wooden roof platform. The Meta Quest Pro headset was used to immerse the participants in the virtual environment.

In this experiment, three distinct virtual roof scenes were created in Unity (V2022.3.34f1) to represent the three roof pitches. Unity is a game engine that is widely used for creating interactive VR experiences, particularly in game development and real-time simulations. The virtual roof scenes included elements of residential house structure, roof covering, a ladder, and scaffolding. Identical surroundings were maintained across all three roof scenes to ensure consistency for participants. Each scene carefully aligned with the physical wooden roof platform before each trial to ensure consistency. The virtual drone model used in this study was a DJI (Shenzhen, China) Mavic 3 Pro, accompanied by a real-world recording of its flight sound. Fig. 2 presents a sample virtual roof scene with the virtual drone used in this study. The development of virtual scenes was carried out on a high-performance workstation equipped with an Intel Core i9-14900K processor (3.20 GHz), 64 GB of RAM, and an NVIDIA GeForce RTX 4080 SUPER graphics card.

Procedure

Upon arrival, participants were briefed on the experiment procedure. They then were given a short training session with the VR headset in the kneeling posture on the force plate to help them become familiarized with the virtual environment. They then read and signed the informed consent forms. Prior to data collection, the VR headset was carefully calibrated to ensure accurate alignment

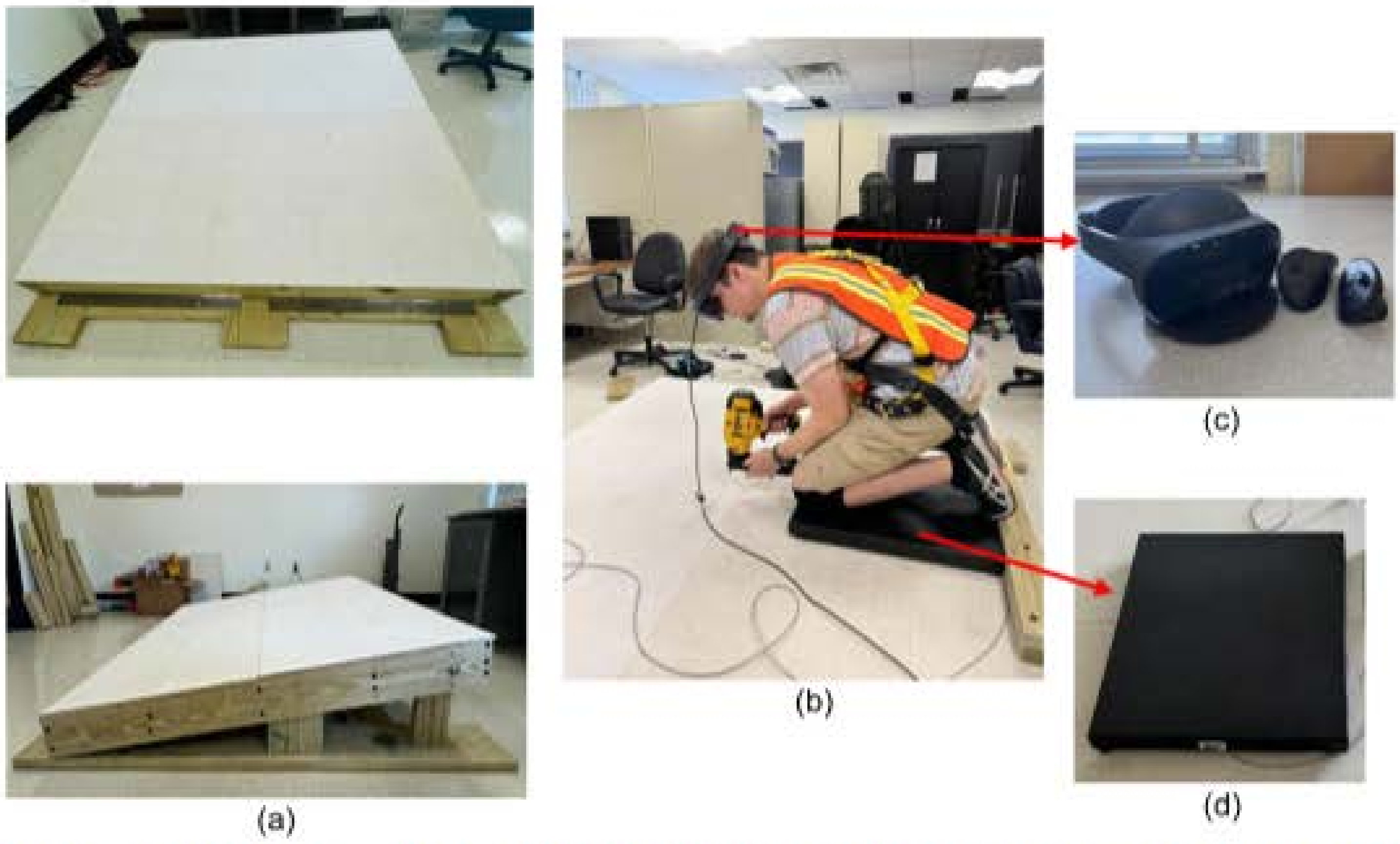

Fig. 1. (a) Simulated wooden roof platform; (b) participant mimicking shingle installation on platform; (c) VR headset; and (d) force plate.

Fig. 2. Virtual roof environment and virtual drone.

Table 1. Drone intrusion and roof pitch settings of scenes

Scenario	Drone intrusion	Roof pitch
1	No drone	0°
2	16 ft	0°
3	48 ft	0°
4	82 ft	0°
5	No drone	3/12
6	16 ft	3/12
7	48 ft	3/12
8	82 ft	3/12
9	No drone	6/12
10	16 ft	6/12
11	48 ft	6/12
12	82 ft	6/12

between the virtual roof scene and the physical wooden roof platform. Additionally, calibration of the force plate was conducted each day based on the manufacturer's instructions and was zeroed before data collection. The force plate was positioned on the roof platform so that the AP direction (y-axis) corresponded to the participant's forward–backward movements, while the ML direction (x-axis) captured their side-to-side sway. To enhance realism, participants were required to wear a high-visibility vest and a fall protection harness, simulating actual construction site conditions. Participants also were required to wear knee pads to ensure comfort during kneeling. Participants then simulated a shingle-nailing task while kneeling on the force plate mounted on the wooden roof platform and wearing a VR headset.

Trials were conducted on the wooden roof platform across three slopes and four drone conditions, resulting in a total of 12 (3×4) scenarios (Table 1). The experiment adopted a repeated measures design, in which each participant went through all testing scenarios. To control the order or sequence effects, the test participants were divided randomly into 12 groups. The order of scenarios was randomized first by slope and then by drone height. Each trial lasted 30 s.

The virtual drone was programmed to take off and hover both in front of and behind the participant. Participants were instructed to maintain a kneeling posture while mimicking a shingle-nailing task by holding a nail gun in their hands. However, they were permitted to react naturally to any distractions caused by the drone's visual or auditory presence. To minimize fatigue and carry-over effects, participants were given a minimum 2-min break between consecutive trials.

Data Processing

Each trial had a duration of 30 s. However, the first 5 s and the last 2 s were excluded from the analysis to minimize the influence of initial transients and participant anticipation. Because the drone appeared in the virtual scene between 8 and 26 s, this timeframe was chosen for analysis to ensure that the focus remained on participants' responses to the drone's presence. A special program was developed using Python (v6, Spyder) to process the data and compute balance parameters from the center of pressure data. Furthermore, to account for differences in knee and foot positioning on the force plate, COP trajectories were centered relative to their arithmetic mean, following common practices in previous studies (Prieto et al. 1996; Qiu and Xiong 2015).

The following balance parameters were calculated:

1. Maximum COP displacement along ML (max ML) and AP (max AP) directions. This feature has been defined as the maximal distance of the COP from the centroid (Muir et al. 2013).
2. RMS, which was calculated in the ML (RMS ML) and AP (RMS AP) direction. It corresponds to the standard deviation of the trajectory (Piirtola and Era 2006; Prieto et al. 1996).
3. The 95% confidence ellipse area, also known as the sway area, which is defined as the area of the ellipse which contains the $(1-\alpha)$% probability of containing the COP of sway (Bendo et al. 2013; Schubert and Kirchner 2014).

Data Analysis

A repeated measures linear mixed model was employed to analyze the effects of drone height and slope on participants' balance, as measured by COP metrics. In this model, test participants were treated as a random effect to account for individual variability, whereas order, scene, previous scene, height, and slope were included as fixed effects. The order variable was included to control for potential learning or fatigue effects, whereas scene and previous scene were incorporated to check carry-over effects.

Type 3 ANOVA was used to evaluate the statistical significance of each fixed effect, specifically focusing on the effects of the drone intrusion and roof slope. In this study, a variable was defined as statistically significant when its p-value was less than 0.05. Post hoc pairwise comparisons were conducted to identify significant differences between conditions. All computations used the lme4 and lmerTest packages in R (Bates et al. 2015; Kuznetsova et al. 2017).

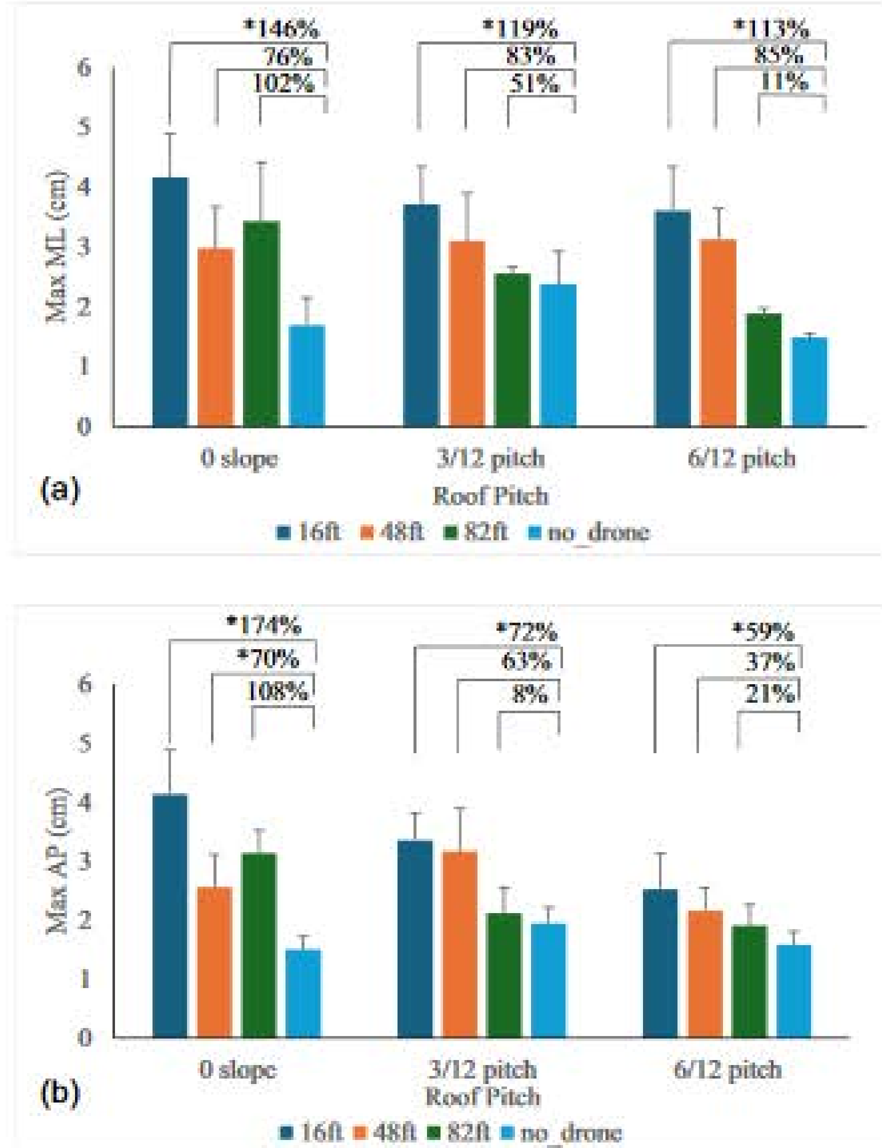

Fig. 3. Average and standard error of mean (error bars) of (a) max ML; and (b) max AP. (* indicates a significant difference from no-drone condition.)

Results

Relative Effects of Drone-Intrusion across Slopes

Mean values of each balance metric under all drone-intrusion conditions at each roof slope for both directions are plotted in Figs. 3–5.

The percentages indicate the effect of drone intrusion at each height relative to the no-drone condition. These percentages were calculated by comparing the mean value of each balance metric at that height with the corresponding mean value under the no-drone condition.

The asterisks (* symbols) indicate statistical significance in comparing drone intrusion heights with the no-drone condition based on the two-sample t-test.

Maximum Distance

Across all roof slopes condition and in both directions (ML and AP), the maximum distance parameter was highest when the drone was at a 16-ft height, and lowest in the absence of the drone (Fig. 3). In the ML direction [Fig. 3(a)], the analysis indicated that when the drone was at 16 ft, it achieved statistical significance for all slope conditions. The maximum distance parameter reached a maximum effect of 146% higher than that of the no-drone condition at 0° slope. The second-highest values were recorded at 82 ft, followed by 48 ft. At 3/12 and 6/12 pitches, the second-highest values were observed at a drone height of 48 ft, and the third-highest values were observed at a drone height of 82 ft.

In the AP direction [Fig. 3(b)], a similar trend was observed to that in the ML direction. The 16-ft drone height had a statistically significant difference from the no-drone condition across all slopes. The maximum effect was observed at 0° slope, for which the 16-ft drone height resulted in a 174% increase compared to the no-drone condition. Additionally, a statistically significant difference also was observed at 48 ft, at which the effect was 70% higher than in the no-drone condition at 0° slope. At 3/12 and 6/12 pitches, the maximum distance parameter was highest when the drone was at 16 ft—119% and 113% higher than in the no-drone condition, respectively, followed by 48- and 82-ft drone heights.

RMS

Fig. 4 shows the trend of RMS values across different slopes and drone heights. At a 0° slope, the RMS ML values exhibited a distinct trend [Fig. 4(a)]. The highest RMS value occurred when the drone was at 82 ft, a 192% increase compared with the no-drone condition, followed by 16 and 48 ft. Notably, all drone heights at this slope had statistically significant differences from the no-drone condition. In contrast, at 3/12 and 6/12 roof pitches, the highest RMS ML values were observed at 16 ft, increases of 45% and 107%, respectively, over the no-drone condition, followed by 48 and 82 ft. However, unlike at the 0° slope, for these pitched roofs none of the drone heights had statistically significant differences from the no-drone condition.

In the AP direction [Fig. 4(b)], the RMS values followed trends similar to other balance metrics. On the 0° slope, the highest RMS values occurred at 16 ft, a 128% increase compared with the no-drone condition, and this difference was statistically significant. Drones at 48 and 82 ft also had significant increases, 49% and 60%, respectively. For the 3/12 and 6/12 roof pitches, the highest RMS values again were observed at 16 ft. At the 3/12 pitch, the 16-ft height resulted in a 59% increase in RMS values compared with the no-drone condition, which was statistically significant. At the steeper 6/12 pitch, RMS values peaked at 16 ft before declining

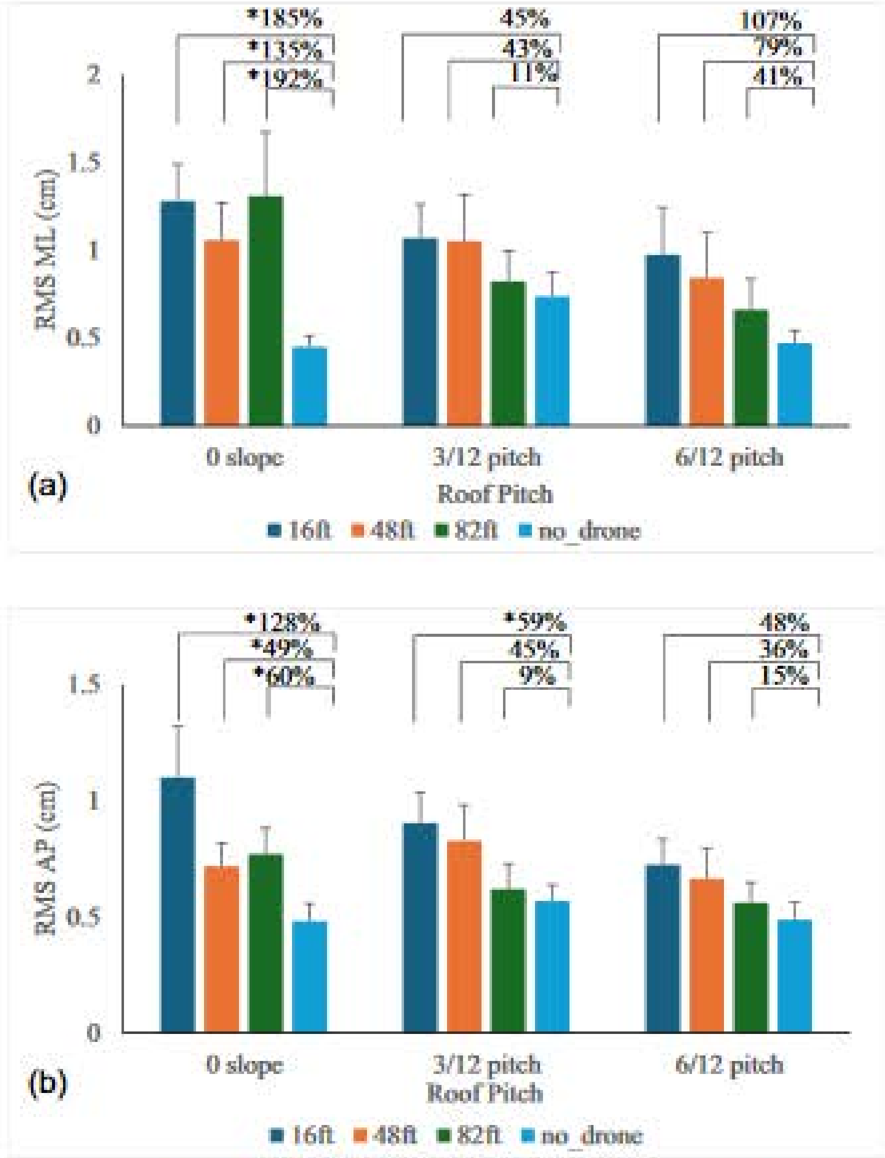

Fig. 4. Average and standard error of mean (error bars) of (a) RMS ML; and (b) RMS AP. (* indicates a significant difference from no-drone condition.)

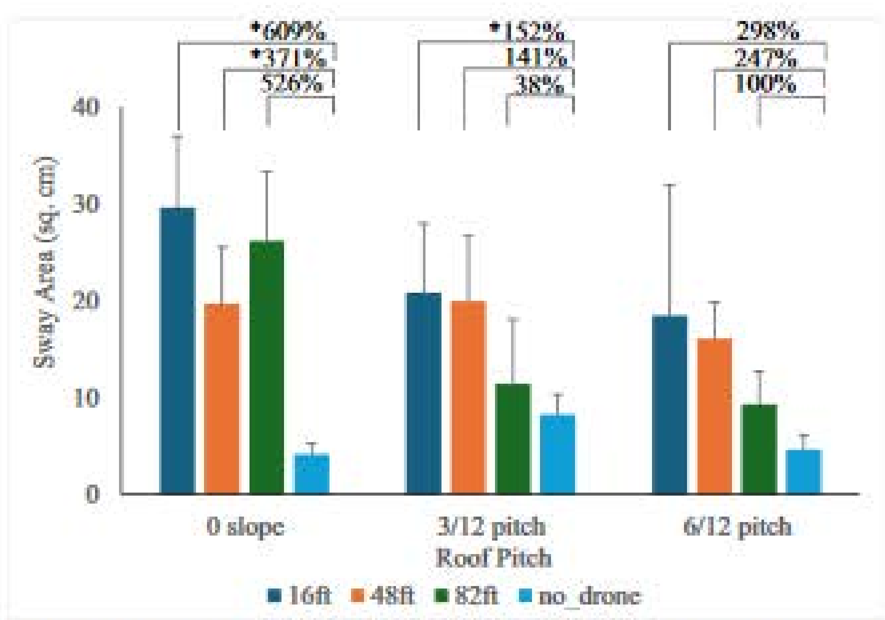

Fig. 5. Average and standard error of mean (error bars) of sway area. (* indicates a significant difference from no drone condition.)

at 48 and 82 ft, and they were lowest in the no-drone condition, although these differences were not statistically significant.

Sway Area

At 0° slope, the sway area was significantly smaller in the no-drone condition than when the drone was at 16 and 48 ft (Fig. 5). The 16-ft drone height resulted in the highest sway area, 6.09 times greater than in the no-drone condition. A statistically significant increase also was observed at 48 ft, for which the sway area was 3.71 times higher than in the no-drone condition. However, at 82 ft, the drone's presence did not lead to a statistically significant difference.

On the 3/12 pitch, the largest sway area was recorded at 16 ft, 1.52 times higher than in no drone condition, followed by 48 ft and then 82 ft. At a 6/12 pitch, no statistically significant differences were found across drone heights. However, the 16-ft drone condition still resulted in the highest sway area, followed by 48 and 82 ft.

Table 2. Results of mixed model

Independent variables	Max ML	Max AP	RMS ML	RMS AP	Sway area
Drone height	<0.001	<0.001	<0.001	<0.001	0.002
Slope	0.428	0.016	0.093	0.072	0.018
Drone height × slope	0.068	0.019	0.4573	0.45453	0.661

Statistical Effects of Slope, Drone-Intrusion, and Their Interaction

Table 2 presents the statistical analysis results. The findings indicate that slope had significant effects on sway area and max AP ($p < 0.05$), whereas drone height had a significant effect on all metrics ($p < 0.05$). No significant interaction effects were observed between drone height and slope for any metrics, except for max AP.

Main Effect of Drone-Intrusion

The pairwise comparisons in Table 3 indicate significant effects of drone intrusion on balance metrics. The presence of a drone at 16 ft had the strongest and most consistent effect, with highly significant differences ($p < 0.005$) across all balance metrics. At 48 ft, the drone also caused notable disturbances, and there were significant differences compared with the no-drone condition. However, at 82 ft, the drone's effect was weaker, and only max AP and sway area had slight but significant increases ($p < 0.05$), suggesting that the impact of drone intrusion diminishes with distance. Comparisons between the 16- and 48-ft conditions indicated significant differences in max ML, max AP, and RMS AP ($p < 0.05$), and the contrast between 16 ft and 82 ft had even stronger effects, with highly significant increases in max ML ($p < 0.005$), max AP ($p < 0.01$), and RMS AP ($p < 0.005$). No significant differences were observed between the 48- and 82-ft conditions, reinforcing the trend that drone-induced instability is more pronounced at lower altitudes.

Main Effect of Roof Slope

The pairwise comparisons between different roof slope conditions in Table 4 indicate several significant differences in postural stability measures. Specifically, the comparison between 0° and 6/12 pitch slopes indicated statistically significant differences in all parameters. In contrast, the comparison between 0° and 3/12 pitch slopes did not yield any significant differences in the measured variables. However, a significant difference was observed in RMS AP displacement ($p < 0.05$) between 3/12 and 6/12 pitch slopes, although no other measures reached significance.

Interaction Effects of Roof Slope and Drone-Intrusion

The interaction effect between slope and drone height was significant only for max AP. No significant interaction was observed for other metrics.

Discussion

The primary aim of this study was to examine how drone intrusion at roofing sites can affect roofers' balance when they are on surfaces

Table 3. Pairwise comparison of drone-intrusion conditions

Drone-intrusion conditions	Max ML	Max AP	RMS ML	RMS AP	Sway area
No drone–16 ft	***	***	***	***	***
No drone–48 ft	**	**	***	**	***
No drone–82 ft	—	*	—	—	*
16 ft–48 ft	*	*	—	*	—
16 ft–82 ft	***	**	—	***	—
48 ft–82 ft	—	—	—	—	—

Note: * $p < 0.05$; ** $p < 0.01$; and *** $p < 0.005$.

Table 4. Pairwise comparison of roof slope conditions

Roof slope	Max ML	Max AP	RMS ML	RMS AP	Sway area
0° – 3/12 pitch	—	—	—	—	—
0° – 6/12 pitch	*	**	*	*	*
3/12 pitch – 6/12 pitch	—	*	—	—	—

Note: * $p < 0.05$; ** $p < 0.01$; and *** $p < 0.005$.

with different slopes. The study included the development of virtual roofing scenes incorporating drones to assess worker postural balance. This is the first study to quantify how drone distraction affects roofers' postural stability during simulated shingle installation on sloped surfaces.

The participants were divided into 12 groups, each assigned a different sequence of scenarios to counterbalance any potential order effects. This design ensured that any influence of scenario order on participants' responses was evenly distributed. The analysis indicated no statistically significant effect of sequence order, indicating that the order in which participants experienced the drone and slope conditions did not impact their responses. Furthermore, there was no significant interaction effect between the order and the current scene (the condition being experienced). This means that the sequence in which participants encountered the scenarios did not influence how they responded to different scenarios.

Additionally, both the current scene and the previous scene (the condition immediately before) were analyzed. The current scene had a statistically significant effect, whereas the previous scene did not. This analysis aimed to detect potential carry-over effects, in which prior exposure could bias subsequent performance. The findings suggest that participants' balance and attention were affected primarily by the present scenario, rather than any residual effects from prior scenarios. This supports the reliability of the results, confirming that the observed effects were driven by the current experimental scenarios rather than carry-over effects from previous exposures.

Two different main factors, roof slope and drone intrusion, were tested to characterize the influence of drone distraction in roofers. Although the effect of slope is not easily controlled in an actual roof environment, it is important to consider how the inclusion of drones at roofing sites will impact roofers' postural stability. There were no statistically significant interactions between slope and drone height. The drone height × slope interaction was tested to determine whether the effect of drone height on roofers' balance depends on the roof slope and vice versa. Because the interaction was not significant, the effects of drone height and roof slope can be interpreted independently, because the effect of one does not depend on the level of the other.

The findings demonstrate that both drone presence and its altitude significantly influenced roofers' postural stability, as reflected in multiple COP measures ($p < 0.005$). The most notable effects were observed at the closest drone proximity (16 ft), at which all balance metrics differed significantly from the no-drone condition. At this distance, maximum COP displacement was highest, indicating that close-range drone distractions led to more-extreme weight shifts to maintain balance. RMS values in both the ML and AP directions further support this finding, indicating greater sway variability during closer drone exposure. Similarly, the increased sway area at this proximity reflects compounded instability, because participants' body sway extended over a larger area, making it harder to maintain stable posture. The 48-ft condition had intermediate effects, which were significantly different from no-drone conditions but not from the 82-ft condition. The 82-ft condition had minimal impact, with only marginal differences from no-drone conditions. Notably, the 16-ft condition also differed from higher altitudes (48 and 82 ft), suggesting that proximity critically exacerbates balance disruption. However, the differences between 48 and 82 ft were not statistically significant across any balance measure, implying that beyond a certain height, the drone's impact diminishes. The visual and auditory distraction caused by the drone may significantly interfere with balance control mechanisms. The closer the drone, the more it diverts workers' attention, impairing their anticipatory adjustments and ability to respond effectively to sudden disturbances. In real-world roofing scenarios, such distractions are likely to increase the risk of slips, loss of balance, and, ultimately, fall-related injuries.

Although drone altitude had clear, significant effects on postural stability, roof slope had more-limited impacts. Although slope did produce statistically significant effects on certain balance metrics, particularly max AP and sway area, its overall influence was less substantial than drone intrusion. However, the effect of slope on balance may not have been as strong as expected, possibly due to the dominant influence of drone distraction. Because drone intrusion had a significant impact on postural stability, it is possible that the presence of drones introduced enough instability that any effect of slope became less detectable. Additionally, the limited sample size may have reduced the statistical power to identify a stronger effect of slope.

Pairwise comparisons indicated that the most notable differences occurred between the 0° surface and the steepest slope (6/12 pitch). Interestingly, participants exhibited greater postural stability as the slope increased. This suggests that individuals were more relaxed and less focused on balance control on flat or low-slope surfaces, consistent with previous findings. Individuals displayed greater caution under high-threat conditions (sloped surfaces) and may have responded by increasing stiffening strategies, which stabilized their posture and reduced sway amplitude. Similar responses have been reported in previous studies, in which postural threat led to improved stability due to adaptive stiffening strategies (Carpenter et al. 2001). Additionally, participants may have perceived the higher friction demands of sloped surfaces and adjusted their behavior to reduce slip risk (Hsiao and Simeonov 2001). However, real-world roofing environments present more dynamic and unpredictable challenges. Failure to recognize slight variations in the friction of a sloped surface, or to maintain safe control over foot speed or the tangential force applied, can lead to a slip (Hsiao and Simeonov 2001). Thus, external distractions such as drones may affect roofers' ability to maintain balance on inclined surfaces, on which heightened focus and precise postural control are essential for stability.

This study presents a repeatable experimental protocol that integrates immersive VR and realistic task simulation to examine the safety implications of drone operations in roofing environments. Shingle installation was selected as the task because it is a common, repetitive, and physically demanding roofing task, during which kneeling is a frequent posture (Breloff et al. 2019). Other activities such as walking between workstations or carrying loads also pose risks for roofers. Future studies could explore these activities. The participants in this study were not professional roofers, but they had internship or employment experience in construction. Novice individuals were chosen to observe the initial balance adjustments that individuals adopt when first exposed to a sloped surface with drone distractions, without relying on strategies developed through roofing experience. Novice workers also are more prone to injuries than are experienced roofers, and hands-on training is particularly important for this group (Grytnes et al. 2021). Although this study is an initial step, it provides an experimental framework that can be used to develop training strategies and guidelines to reduce drone-related risks for roofers.

This study provides insights into how drone inclusion at roofing sites affects roofers' balance on sloped surfaces. However, there are some limitations. First, the current VR environment lacks certain physical elements, including wind disturbances and variations in rotor noise, which could influence workers' reactions. Second, this study utilized only one type of virtual drone in the experiment. Because drones differ in size, sound, and intended use, these variations could impact the level of distraction. Third, the relatively small sample size and variability in demographics, including ethnicity, as well as comfort with simulated tasks, may have influenced the results. Lastly, this study focused solely on the kneeling posture, whereas roofers adopt various postures while installing shingles. However, exploring these additional factors and their effects was beyond the scope of this study. Despite these limitations, this study offers an important contribution by being one of the first to systematically evaluate how drone-related distractions affect roofers' postural stability, and it highlights the need to consider drone presence in roofer safety. The study developed a generalizable experimental protocol that can serve as a foundation for future research. Future studies can build on this protocol by incorporating additional factors to gain a more comprehensive understanding of the impact of drones on roofers' balance.

Conclusions

This VR-based study investigated the effects of drone proximity and roof slope on roofers' postural stability. Drones were found to distract roofers and reduce task focus, and closer drone proximity caused greater distractions and balance disturbances. These findings highlight the need to establish safety protocols, such as minimum flyover distances or restricted drone operations during critical tasks, to mitigate fall risks in roofing environments. The study provides foundational insights for developing guidelines for safe drone integration at roofing sites.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

This study was supported by the National Institute for Occupational Safety and Health (NIOSH) under Project #1R21OH012455-01A1. The authors are grateful to Dr. Steven Cain at WVU for his assistance with the force plate used in this study, and to the participants who voluntarily participated in the experiment. The findings and conclusions presented in this paper are those of the authors and do not necessarily reflect the official position of NIOSH, Centers for Disease Control and Prevention.

Author Contributions

Mahfuza Maisha Mouri: Data curation; Formal analysis; Investigation; Software; Visualization; Writing – original draft. Wei Han: Investigation; Software. Liqun Xu: Investigation. Alireza Ghasemi: Data curation; Investigation. Wei-Yin Loh: Formal analysis; Supervision; Writing – review and editing. Zhenhua Zhu: Funding acquisition; Supervision; Writing – review and editing. Fei Dai: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Writing – review and editing.

References

Adjidjonu, D., and J. Burgett. 2021. "Assessing the accuracy of unmanned aerial vehicles photogrammetric survey." *Int. J. Construct. Educ. Res.* 17 (1): 85–96. https://doi.org/10.1080/15578771.2020.1717683.

Albeaino, G., P. Brophy, M. Gheisari, R. R. Issa, and I. Jeelani. 2022. "Working with drones: Design and development of a virtual reality safety training environment for construction workers." In *Proc., Computing in Civil Engineering 2021*, 1335–1342. Reston, VA: ASCE.

Albeaino, G., P. Brophy, I. Jeelani, M. Gheisari, and R. R. Issa. 2023. "Impact of drone presence on construction individuals working at heights." *J. Constr. Eng. Manage.* 149 (11): 04023119. https://doi.org/10.1061/JCEMD4.COENG-13861.

Bates, D., M. Mächler, B. Bolker, and S. Walker. 2015. "Fitting linear mixed-effects models using lme4." *J. Stat. Software* 67 (Oct): 1–48. https://doi.org/10.18637/jss.v067.i01.

Bendo, A., S. Kuvarati, D. Skënderi, and A. Veveçka. 2013. "A theoretical study on the evaluation of the stability and postural sway, based on the results of confidence ellipse." *Int. J. Sci. Res.* 6 (14): 1776–1779. https://doi.org/10.21275/SUB15608.

Breloff, S. P., E. W. Sinsel, A. Dutta, R. E. Carey, C. M. Warren, F. Dai, S. Ning, and J. Z. Wu. 2019. "Are knee savers and knee pads a viable intervention to reduce lower extremity musculoskeletal disorder risk in residential roofers?" *Int. J. Ind. Ergon.* 74 (Nov): 102868. https://doi.org/10.1016/j.ergon.2019.102868.

Bureau of Labor Statistics. 2024. "Occupational outlook handbook, roofers." Accessed February 20, 2024. https://www.bls.gov/ooh/construction-and-extraction/roofers.htm.

Calantropio, A. 2019. "The use of UAVs for performing safety-related tasks at post-disaster and non-critical construction sites." *Safety* 5 (4): 64. https://doi.org/10.3390/safety5040064.

Carpenter, M. G., J. S. Frank, C. P. Silcher, and G. W. Peysar. 2001. "The influence of postural threat on the control of upright stance." *Exp. Brain Res.* 138 (May): 210–218. https://doi.org/10.1007/s002210100681.

Cheng, J.-Y., M. Gheisari, and I. Jeelani. 2023. "Using 360-degree virtual reality technology for training construction workers about safety challenges of drones." *J. Comput. Civ. Eng.* 37 (4): 04023018. https://doi.org/10.1061/JCCEE5.CPENG-5140.

Chinchane, A., and S. Mutreja. 2024. *Construction drone market: Global opportunity analysis and industry forecast, 2023–2032*, 192. Wilmington, DE: Allied Market Research.

Cleworth, T. W., B. C. Horslen, and M. G. Carpenter. 2012. "Influence of real and virtual heights on standing balance." *Gait Posture* 36 (2): 172–176. https://doi.org/10.1016/j.gaitpost.2012.02.010.

Costa, D. B., and A. T. Mendes. 2016. "Lessons learned from unmanned aerial system-based 3D mapping experiments." In *Proc., 52nd ASC Annual Int. Conf.* Provo, UT: Associated Schools of Construction.

Eiris, R., G. Albeaino, M. Gheisari, W. Benda, and R. Faris. 2021. "InDrone: A 2D-based drone flight behavior visualization platform for indoor building inspection." *Smart Sustainable Built Environ.* 10 (3): 438–456. https://doi.org/10.1108/SASBE-03-2021-0036.

Finn, R. L., and D. Wright. 2012. "Unmanned aircraft systems: Surveillance, ethics and privacy in civil applications." *Comput. Law Secur. Rev.* 28 (2): 184–194. https://doi.org/10.1016/j.clsr.2012.01.005.

Fleming, M., and B. Fischer. 2017. "Hazard recognition." *Prof. Saf.* 62 (6): 52–61.

Fredericks, T. K., O. Abudayyeh, S. D. Choi, M. Wiersma, and M. Charles. 2005. "Occupational injuries and fatalities in the roofing contracting industry." *J. Constr. Eng. Manage.* 131 (11): 1233–1240. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:11(1233).

Geurts, A. C., B. Nienhuis, and T. W. Mulder. 1993. "Intrasubject variability of selected force-platform parameters in the quantification of postural control." *Arch. Phys. Med. Rehabil.* 74 (11): 1144–1150. https://doi.org/10.1016/S0003-9993(23)00004-7.

Grytnes, R., M. L. Nielsen, A. Jørgensen, and J. Dyreborg. 2021. "Safety learning among young newly employed workers in three sectors: A challenge to the assumed order of things." *Saf. Sci.* 143 (Nov): 105417. https://doi.org/10.1016/j.ssci.2021.105417.

Hsiao, H., and P. Simeonov. 2001. "Preventing falls from roofs: A critical review." *Ergonomics* 44 (5): 537–561. https://doi.org/10.1080/00140130110034480.

Hu, B., S. Xia, Z. Zhu, J.-Y. Cheng, Y. Luo, I. Jeelani, and M. Gheisari. 2025. "Exploring the effect of human-drone communication modality on safety and balance control in virtual construction environments." *Ergonomics* 68 (5): 723–736. https://doi.org/10.1080/00140139.2024.2380342.

Ibrahim, A., and M. Golparvar-Fard. 2019. "4D BIM based optimal flight planning for construction monitoring applications using camera-equipped UAVs." In *Proc., ASCE Int. Conf. on Computing in Civil Engineering 2019*, 217–224. Reston, VA: ASCE.

Izadi Moud, H., I. Flood, X. Zhang, B. Abbasnejad, P. Rahgozar, and M. McIntyre. 2021. "Quantitative assessment of proximity risks associated with unmanned aerial vehicles in construction." *J. Manage. Eng.* 37 (1): 04020095. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000852.

Jeelani, I., and M. Gheisari. 2022. *Safety challenges of UAV integration in the construction industry: Focusing on workers at height.* Gainesville, FL: Univ. of Florida.

Johnson, W. E. 1976. *Roofers handbook.* Solana Beach, CA: Craftsman Book Company.

Karakhan, A. A., and M. Al-Mhdawi. 2024. "Risks associated with using drones in construction for safety management." *Pract. Period. Struct. Des. Constr.* 29 (4): 06024002. https://doi.org/10.1061/PPSCFX.SCENG-1543.

Khalid, M., M. Namian, and C. Massarra. 2021. "The dark side of the drones: A review of emerging safety implications in construction." *EPiC Ser. Built Environ.* 2 (1): 18–27. https://doi.org/10.29007/x3vt.

Kuznetsova, A., P. B. Brockhoff, and R. H. Christensen. 2017. "lmerTest package: Tests in linear mixed effects models." *J. Stat. Software* 82 (Dec): 1–26. https://doi.org/10.18637/jss.v082.i13.

Li, Y., and C. Liu. 2019. "Applications of multirotor drone technologies in construction management." *Int. J. Construct. Manage.* 19 (5): 401–412. https://doi.org/10.1080/15623599.2018.1452101.

Martinez, J. G., M. Gheisari, and L. F. Alarcón. 2020. "UAV integration in current construction safety planning and monitoring processes: Case study of a high-rise building construction project in Chile." *J. Manage. Eng.* 36 (3): 05020005. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000761.

McCabe, B. Y., H. Hamledari, A. Shahi, P. Zangeneh, and E. R. Azar. 2017. "Roles, benefits, and challenges of using UAVs for indoor smart construction applications." In *Proc., Computing in Civil Engineering 2017*, 349–357. Reston, VA: ASCE. https://doi.org/10.1061/9780784480830.043.

Merlo, A., D. Zemp, E. Zanda, S. Rocchi, F. Meroni, M. Tettamanti, A. Recchia, U. Lucca, and P. Quadri. 2012. "Postural stability and history of falls in cognitively able older adults: The Canton Ticino study." *Gait Posture* 36 (4): 662–666. https://doi.org/10.1016/j.gaitpost.2012.06.016.

Morgenthal, G., and N. Hallermann. 2014. "Quality assessment of unmanned aerial vehicle (UAV) based visual inspection of structures." *Adv. Struct. Eng.* 17 (3): 289–302. https://doi.org/10.1260/1369-4332.17.3.289.

Moud, H. I., I. Flood, A. Shojaei, Y. Zhang, X. Zhang, M. Tadayon, and M. Hatami. 2019. "Qualitative assessment of indirect risks associated with unmanned aerial vehicle flights over construction job sites." In *Proc., ASCE Int. Conf. on Computing in Civil Engineering 2019*, 83–89. Reston, VA: ASCE. https://doi.org/10.1061/9780784482445.011.

Muir, J. W., D. P. Kiel, M. Hannan, J. Magaziner, and C. T. Rubin. 2013. "Dynamic parameters of balance which correlate to elderly persons with a history of falls." *PLoS One* 8 (8): e70566. https://doi.org/10.1371/journal.pone.0070566.

Opfer, N. D., and D. R. Shields. 2014. "Unmanned aerial vehicle applications and issues for construction." In *Proc., 2014 ASEE Annual Conf. and Exposition*, 1301–1324. Washington, DC: American Society for Engineering Education.

Palmieri, R. M., C. D. Ingersoll, M. B. Stone, and B. A. Krause. 2002. "Center-of-pressure parameters used in the assessment of postural control." *J. Sport Rehabil.* 11 (1): 51–66. https://doi.org/10.1123/jsr.11.1.51.

Parsons, T. J., and T. J. Pizatella. 1984. *Safety analysis of high risk activities within the roofing industry.* Springfield, VA: National Technical Information Service.

Piirtola, M., and P. Era. 2006. "Force platform measurements as predictors of falls among older people—A review." *Gerontology* 52 (1): 1–16. https://doi.org/10.1159/000089820.

Prieto, T. E., J. B. Myklebust, R. G. Hoffmann, E. G. Lovett, and B. M. Myklebust. 1996. "Measures of postural steadiness: Differences between healthy young and elderly adults." *IEEE Trans. Biomed. Eng.* 43 (9): 956–966. https://doi.org/10.1109/10.532130.

Qiu, H., and S. Xiong. 2015. "Center-of-pressure based postural sway measures: Reliability and ability to distinguish between age, fear of falling and fall history." *Int. J. Ind. Ergon.* 47 (May): 37–44. https://doi.org/10.1016/j.ergon.2015.02.004.

Rakha, T., and A. Gorodetsky. 2018. "Review of unmanned aerial system (UAS) applications in the built environment: Towards automated building inspection procedures using drones." *Autom. Constr.* 93 (Sep): 252–264. https://doi.org/10.1016/j.autcon.2018.05.002.

Ruser, J. 1995. *A relative risk analysis of workplace fatalities, fatal workplace injuries in 1993: A collection of data and analysis.* Rep. No. 891. Washington, DC: US Bureau of Labor Statistics.

Schubert, P., and M. Kirchner. 2014. "Ellipse area calculations and their applicability in posturography." *Gait Posture* 39 (1): 518–522. https://doi.org/10.1016/j.gaitpost.2013.09.001.

Simeonov, P. I., H. Hsiao, B. W. Dotson, and D. E. Ammons. 2003. "Control and perception of balance at elevated and sloped surfaces." *Hum. Factors* 45 (1): 136–147. https://doi.org/10.1518/hfes.45.1.136.27232.

Szóstak, M., A.-M. Mahamadu, A. Prabhakaran, D. C. Pérez, and K. Agyekum. 2024. "Development and testing of immersive virtual reality environment for safe unmanned aerial vehicle usage in construction scenarios." *Saf. Sci.* 176 (Aug): 106547. https://doi.org/10.1016/j.ssci.2024.106547.

Tatum, M. C., and J. Liu. 2017. "Unmanned aircraft system applications in construction." *Procedia Eng.* 196 (Jan): 167–175. https://doi.org/10.1016/j.proeng.2017.07.187.

Unger, J., M. Reich, and C. Heipke. 2014. "UAV-based photogrammetry: Monitoring of a building zone." *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* XL-5 (5): 601–606. https://doi.org/10.5194/isprsarchives-XL-5-601-2014.

Wade, C., and J. Davis. 2009. "Postural sway following prolonged exposure to an inclined surface." *Saf. Sci.* 47 (5): 652–658. https://doi.org/10.1016/j.ssci.2008.09.002.

Wang, P., P. Wu, J. Wang, H.-L. Chi, and X. Wang. 2018. "A critical review of the use of virtual reality in construction engineering education and training." *Int. J. Environ. Res. Public Health* 15 (6): 1204. https://doi.org/10.3390/ijerph15061204.

Whyte, J. 2003. "Industrial applications of virtual reality in architecture and construction." *J. Inf. Technol. Constr.* 8 (4): 43–50.

Yildiz, S., S. Kivrak, and G. Arslan. 2021. "Using drone technologies for construction project management: A narrative review." *J. Constr. Eng. Manage. Innovation* 4 (4): 229–244. https://doi.org/10.31462/jcemi.2021.04229244.

Zhou, S., and M. Gheisari. 2018. "Unmanned aerial system applications in construction: A systematic review." *Constr. Innovation* 18 (4): 453–468. https://doi.org/10.1108/CI-02-2018-0010.

Zhu, Z., I. Jeelani, and M. Gheisari. 2022. "Safety risk assessment of drones on construction sites using 4D simulation." In *Proc., Int. Symp. on Automation and Robotics in Construction*. Oulu, Finland: International Association for Automation and Robotics in Construction.

Zhu, Z., I. Jeelani, and M. Gheisari. 2023. "Physical risk assessment of drone integration in construction using 4D simulation." *Autom. Constr.* 156 (Dec): 105099. https://doi.org/10.1016/j.autcon.2023.105099.