Tendency surveys of drone-related accidents and evaluation of the effectiveness of protective equipment

Ayumu Miyahara[1], Kosuke Yoshizaki[1], Soto Moreno Johan Alexis[1], Kengo Takahashi[1], Hiroki Igarashi[2], Toshiro Hoshi[1], Tetsuya Kimura[1]

1 Nagaoka University of Technology
1603-1 Kamitomioka, Nagaoka, Niigata 940-2188, Japan
2 Department of Aeronautics and Astronautics, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

KEYWORDS: Drone, UAS, UAV, Propeller, Risk Reduction, NEISS, Plane, Helicopter, PPE

ABSTRACT

Introduction The widespread use of unmanned aircraft systems (UAS), commonly referred to as drones, has led to various accidents and injuries. Therefore, the use of UAS requires appropriate management to ensure worker safety. However, instruction manuals of commercial UAS do not sufficiently explain the risks associated with their use and corresponding countermeasures, making it difficult to assess and reduce risks. Therefore, we investigated drone-related accidents to provide basic information for users for assessing risks. Furthermore, we clarify the effectiveness of protective equipment through experiments wherein a propeller collides with the protective equipment.

Methods We extracted accident-related data from National Electronic Injury Surveillance System, operated by the Consumer Product Safety Commission in the United States, by searching the narrative column for multiple keywords related to drones and then classifying them. To evaluate the effectiveness of protective equipment, cut-resistant gloves, eyewear, and helmets were struck by a rotating propeller.

Results We obtained data on 400 accidents (415 injuries) that occurred between 2010 and 2022; after reaching a peak (45 cases) in 2016, the number decreased. Among them, 74 (18.5%) occurred during drone operation, 48 (12%) during preparation/tidying up/repair/adjustment, and 18 (4.5%) during hand catch/launch. Additionally, 37 (9.3%) involved other accidents, such as falling while trying to retrieve a drone caught in a tree. When categorized by injury, 219 (52.8%) involved lacerations or amputations of fingers, 51 (12.3%) involved lacerations of arms, and 28 (6.7%) involved lacerations of face, including the eyes. Moreover, in 380 (95%) cases, the victims were discharged from the hospital after treatment/examination and were therefore presumed to have minor injuries. Furthermore, the probability of finger amputations was high when using a UAS with propeller diameter ≥ 15 in without cut-resistant gloves; however, wearing cut-resistant gloves compliant with EN388 and other standards reduces the possibility of amputation. However, for propeller diameters > 20 in, finger amputation/fracture occurred even when wearing cut-resistant gloves. Additionally, eye protection compliant with standards such as ANSI Z87.1 with fixation straps have effectively reduced injury risk for propellers up to 20 in in diameter. However, eyewear without straps is easily damaged or falls offs when hit by smaller propellers from the side. We did not identify any instances of a 20 in propeller penetrating the top of helmets compliant with the EN 397 standard.

Conclusions Although the number of drone-related accidents is decreasing, the potential for serious accidents, such as finger amputations and blindness, remains neglected. We confirmed that protective equipment, such as gloves, eyewear, and helmets, can reduce risks to a certain extent; however, the negative impact of protective equipment on control performance is unknown. Considering that UAS with propellers > 20 in are commercially available, it is necessary to consider more effective safety measures against drone-related injuries. Moreover, the standards referenced in the collision tests do not define the performance of protective equipment for drone collisions. Therefore, new methods and standards are required to evaluate and develop protective equipment for drone collisions.

1 INTRODUCTION

Unmanned fixed-wing aircrafts, helicopters, and multicopters, commonly referred to as unmanned aircraft system (UAS) or drones, are widely used globally. However, accidents wherein drones or their propellers collide with people have occurred. To address this, studies have statistically investigated accidents and evaluated their degree of harm [1] [2] [3] [4] [5] [6]. Additionally, a survey found that 47% of commercial drone users wear helmets [7]. However, few studies have evaluated the effectiveness of personal protective equipment (PPE), which include gloves, eyewear, caps, and helmets, against drone-related accidents. This study aimed to assess the accident tendency and situations of UAS and the effectiveness of PPE by using National Electronic Injury Surveillance System (NEISS) data and conducting crash experiments to clarify the situations wherein accidents occur and the type of PPE that drone users should wear to ensure their safety.

2 BACKGROUND

2.1 Accident cases and investigations

Several accidents wherein drones or their propellers have collided with people have occurred. In 2013, a man died after a radio-controlled helicopter clipped the top of his head and another suffered a fractured skull after a drone hit him in the head [8] [9]. In 2014, a multicopter hit a woman's head and received three stitches [10]. In 2015, a drone propeller severed a toddler's eye [11]. In 2016, a boy suffered a ruptured eyeball when a drone propeller hit his eye, and a girl experienced bleeding and abrasion in her eye when hit by a drone hit [12]. In 2017, a woman was killed when an airplane crashed into her head [13]. In 2018, the propeller of a multicopter contacted a man's head, resulting in forehead laceration and bleeding and lacerations in the left eye [14]. In 2021, a boy partly lost his vision and a man lost vision in his right eye after being hit by drone propellers in their eyes, and another suffered a laceration and fractured a finger bone when a vertical take-off and landing aircraft propeller hit his hand [15] [16] [17].

A statistical study of these drone-related accidents estimated 12,842 accidents involving hobby aircraft in the U.S. from 2010–2017 [1]. A study focusing exclusively on children found that drones primarily resulted in head and face injuries [18].

2.2 Positioning of this study

Studies wherein drones were crashed into dummy dolls identified cases of injury when drones weighing either 3.1 kg or 11 kg were crashed. [2]. A study of drone impacts on postmortem human surrogates showed that the direction and location of the impact significantly affect the energy transfer [3]. Another study that tested propeller crashes on pigs confirmed that they could also damage bones [4] [5]. Similarly, a study using fetal bovine skin confirmed a correlation between propeller velocity and injury severity [6].

Thus, many studies have investigated the injuries caused by drones and their propellers. However, few studies have proposed the safety measures for reducing injuries, and even drone manuals do not adequately explain them. Some studies have evaluated the effects of propeller collisions with PPE and confirmed that existing PPE can potentially reduce propeller-related injuries [19] [20].

Therefore, to clarify when and the type of PPE that can ensure the safety of drone users, we verified the accident tendencies and situations and the effects of PPE using case data from the NEISS and through collision experiments between PPE and propellers.

3 SURVEY USING NEISS DATA

3.1 Method

This study employed NEISS data from 2010–2022. NEISS collects information on consumer product-related injuries occurring in the United States, including the body part, type of injury, narrative, and related product-specific codes (Consumer Product Safety Commission Product codes) for cases handled by hospital emergency departments. Drones are included under 5021 (Toy vehicles) and do not have a dedicated code. Additionally, some drone-related cases employ different codes; therefore, the narrative column was searched using multiple keywords related to drones, as shown in *Table 1*. We read and classified the narrative columns of the cases obtained through the search to identify drone-related accidents. Furthermore, we used the same keywords as those used in a previous study [1], in addition to unmanned aerial vehicle (UAV) and UAS, as defined by the FAA (Federal Aviation Administration) [21].

3.2 Results

The NEISS recorded 400 drone-related accidents between 2010 and 2022, of which 363 were caused by a drone or its propeller contacting a human. The remaining 37 accidents involved individuals falling while retrieving drones stuck in trees. *Table 2* and *Table 3* present the classification results of these accidents according to the injury type and body part, whereas *Table 4* presents their classification results according to the circumstances at the time of their occurrence. The total number of injuries is greater than the total number of accidents, because multiple injuries occurred in 11 of the 363 and 4 of the 37 accidents. (415 injuries occurred in 400 accidents)

Table 1 Keywords used in the search

Keywords	Related terms
Radio con	Radio control, Radio controlled
Radio-con	Radio control, Radio controlled
Remote con	Remote control, Remote controlled
Remote-con	Remote control, Remote controlled
Model air	Model aircraft, Model airplane
Model-air	Model aircraft, Model airplane
Heli	Helicopter
Plane	Plane, Airplane
Toy air	Toy aircraft, Toy airplane
Propel	Propeller
Drone	Drone
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle

Table 2 Injury types and body parts injured directly related to drone or propeller collisions

	Eyeball, Face N (%)	Head, Ear, Neck, Mouth N (%)	Hand, Finger, Wrist N (%)	Upper/Lower arm, Elbow N (%)	Upper/Lower trunk, Shoulder N (%)	Upper/Lower leg, Knee, Foot, Ankle, Toe N (%)
Amputation	0	0	12 (2.9)	0	0	0
Avulsion	0	0	4 (1.0)	0	0	1 (0.2)
Contusion, Abrasions	15 (3.6)	0	4 (1.0)	1 (0.2)	0	1 (0.2)
Fracture	1 (0.2)	0	8 (1.9)	0	1 (0.2)	1 (0.2)
Internal organ injury	0	5 (1.2)	0	0	0	0
Laceration	**25 (6.0)**	13 (3.1)	**205 (49.4)**	**51 (12.3)**	1 (0.2)	18 (4.3)
Strain, Sprain	0	0	1 (0.2)	0	0	0
Hematoma	0	0	1 (0.2)	0	0	0
Others, Not Stated	5 (1.2)	0	0	0	0	0
Total	46 (11.1)	18 (4.3)	235 (56.6)	52 (12.5)	2 (0.5)	21 (5.1)
	374 injuries (90.1) (363 accidents)					

Table 3 Injury type and body part injured indirectly related to drone collisions

	Eyeball, Face N (%)	Head, Ear, Neck, Mouth N (%)	Hand, Finger, Wrist N (%)	Upper/Lower arm, Elbow N (%)	Upper/Lower trunk, Shoulder N (%)	Upper/Lower leg, Knee, Foot, Ankle, Toe N (%)	Over 50% of body N (%)
Amputation	0	0	0	0	0	0	0
Avulsion	0	0	0	0	0	0	0
Contusions, Abrasions	1 (0.2)	1 (0.2)	0	2 (0.5)	1 (0.2)	0	0
Fracture	1 (0.2)	1 (0.2)	1 (0.2)	1 (0.2)	0	**4 (1.0)**	0
Internal organ injury	0	1 (0.2)	0	0	0	0	0
Laceration	**3 (0.7)**	**3 (0.7)**	2 (0.5)	0	0	2 (0.5)	0
Strain, Sprain	0	0	0	0	0	**7 (1.7)**	0
Burns electrical	0	0	1 (0.2)	0	0	0	0
Dislocation	0	0	0	0	0	1 (0.2)	0
Foreign body	0	0	0	0	0	1 (0.2)	0
Electrical shock	0	0	0	0	0	0	2 (0.5)
Dental injury	0	1 (0.2)	0	0	0	0	0
Others, Not Stated	0	0	0	0	2 (0.5)	2 (0.5)	0
Total	5 (1.2)	7 (1.7)	4 (1.0)	3 (0.7)	3 (0.7)	17 (4.1)	2 (0.5)
	41 injuries (9.9) (37 accidents)						

Table 4 Situation when the accident occurred

Injuries caused by drone or propeller collisions N (%)	Self-operated	**74 (18.5)**
	Operated by someone else	17 (4.3)
	Repairing/adjusting/cleaning up	**48 (12.0)**
	During takeoff/landing (including hand launch/catch)	18 (4.5)
	Not stated	206 (51.5)
	Total	363
Injuries indirectly related drones N (%)	Falling/tripping while operating a drone	**12 (3.0)**
	Falling/jumping while recovering a drone	**13 (3.3)**
	Falling object/protrusion while recovering a drone	9 (2.3)
	Electric shock while recovering a drone	3 (0.8)
	Total	37

Focusing on injuries resulting from drone or propeller collisions, 49.4% included hand lacerations, 12.3% included arm or elbow lacerations, and 6.0% included eye or face lacerations. Additionally, 18.5% occurred during maneuvering and 12.0% occurred during repair. Examining injuries indirectly related to drones, 1.7% included leg sprains or strains and 1.0% involved leg fractures. Furthermore, 3.3% were caused by falling or jumping while retrieving a drone caught in a tree or other object, and 3.0% were caused by falling or tripping while operating a drone. Finally, 185 injuries (174 accidents) involved drone propellers, of which 85.4% included lacerations.

4 EXPERIMENTS

Protective gloves and eyewear are considered effective PPE to prevent injuries caused by collisions with drones or their propellers. Conventional PPE is designed for impact from falling objects and falls. However, few studies have verified the effectiveness of PPE against injuries caused by drone propellers and some have conducted experiments wherein PPE was subjected to collisions with rotating propellers [19] [20]. In this section, we examine the PPE that can effectively protect users drone-propeller-related injuries based on the results of previous studies and collision experiments conducted in this study. Moreover, a survey of commercial drone users found that 47% of the users wear helmets; therefore, crash tests using helmets were also conducted [7].

4.1 Experimental method

The PPE used in the experiment is shown in *Figure 1*. They included protective gloves of Levels 1, 3, and 5 as specified by the EN388:2003 standard. The hand model was made of silicone and a wooden rod that simulated muscles and bone hardness. The eyewear was compliant with such as the ANSI Z87.1 standard, whereas the head PPE conformed to the EN812 and EN397 standards. The head model was made of vinyl.
As shown in *Figure 2*, we used with diameters of 15 and 20 in, which have been confirmed to be capable of completely severing a finger [20].
Figure 3 presents an overview of the experimental system comprising a drone model, trolley, launcher, high-speed camera, and PPE. During the launch, the propeller was run at its maximum speed (approximately 6,000–8,000 rpm) and the launcher accelerated the trolley carrying the drone to 2 m/s. At the end of the launcher, the stopper caught trolley and launched the drone model, causing the propeller to impact the PPE. The impact was captured using a high-speed camera at approximately 8,000–15,000 fps.

PPE				
Standard	EN388:2003 Level 1	EN388:2003 Level 3	EN388:2003 Level 5	N/A
PPE				
Standard	ANSI Z87.1+, EN166(F) MIL-662F, STANAG 2920	ISO 4007:2012, ISO 4849:1981 ISO 4854:1981, ISO 4855:1981MOD	EN812:2012	EN397:2012, EN12492:2012, ANSI Z87.1

Figure 1 PPE used in the experiment

Diameter [inch]	Material	Weight [g]	External view
15	Carbon fiber	21	
20	Carbon fiber	58	

Figure 2 Propellers used in the experiment

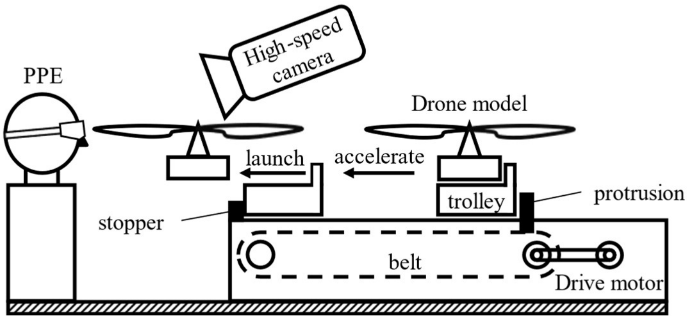

Figure 3 Experimental System

4.2 Results

Figure 4 to *Figure 10* show examples of the results of the collision experiment. *Figure 4* and *Figure 5* show the impact results of the 15 in propeller on ungloved and gloved (EN388:2003 Level 1) hand models, respectively, whereas *Figure 6* shows that on eyewear that does not comply with the ANSI or other standards. *Figure 7* and *Figure 8* show impact results of 15 and 20-in propellers, respectively, on eyewear compliant with ANSI and other standards, whereas *Figure 9* and *Figure 10* show those of the 20-in propeller on helmets conforming to EN812 and EN397 standards, respectively.

As shown in *Figure 4*, there is a high possibility of finger amputation with the 15-in propeller if gloves were not worn; however, no amputation occurred when using gloves complying with the EN388 standard, as shown in *Figure 5*. Previous studies have shown that wound length decreases as the EN388 level increases, and propellers over 20 in can result in finger amputation or fracture, even when wearing EN388-compliant gloves [20].

As shown in *Figure 6*, eyewear that did not conform to any standard was destroyed by propeller impact. Moreover, as shown in *Figure 7*, the lenses of eyewear compliant with existing ANSI and other standards detached from the frame or the eyewear fell off when struck by the propeller from the side. However, the eyewear secured with a belt did not fall off, as shown in *Figure 8*.

As shown in *Figure 9*, the bump cap was damaged by propeller impact. Moreover, as shown in *Figure 10*, the side of the helmet complying with the more stringent standard (EN 397) was penetrated by the 20-in propeller, but the propeller did not contact the head and. he helmet top was not penetrated.

5 DISCUSSIONS

Protective gloves are effective against propeller-related injuries because they prevented or reduced finger amputations and lacerations caused by both 15- and 20-in propellers in the crash tests. Additionally, eyewear that conforms to ANSI or other standards and includes a band that prevents it from falling off the head is effective. Furthermore, helmets compliant with the EN397 standard are effective against propeller-induced injuries, as no head injuries occurred even when the helmet was penetrated. Drone collisions involve collisions of flying or falling objects that are conventionally assumed by PPE. Based on these results, hand, eye, and head lacerations, which account for 49.4, 6.0, and 3.1% of the injuries caused by direct contact with the drone or its propeller, respectively, can be reduced by wearing protective gloves, eyewear with bands, and helmets. These protective devices can also reduce hand, eye, and head lacerations caused by accidents indirectly related to drones. However, the PPE evaluated in this study cannot prevent arm injuries; therefore, future studies must consider PPE for arms.

The most common situation in which an accident occurred was maneuvering, followed by repair, which can be effectively reduced by using PPE. However, the adverse effects of PPE on work accuracy and efficiency remain unknown and should be evaluated in the future.

The PPE used in this study was not designed for drone or propeller collisions. Although the eyewear and helmets conformed to existing standards, their effectiveness varied based on the direction of impact. Therefore, to accurately evaluate and develop PPE that can mitigate the risks posed by drone and propeller collisions, it is necessary to develop evaluation methods and standards by considering such collisions.

Figure 4 Finger amputated.
Glove: N/A, Propeller: 15 in

Figure 5 Finger not amputated.
Standard: EN388 Level 1, Propeller: 15 in

Figure 6 Eyewear broken.
Standard: N/A, Propeller: 15 in

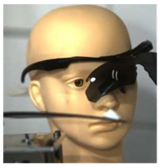

Figure 7 Eyewear dislodged.
Standard: ANSI Z87.1+, Propeller: 15 in

Figure 8 Eyewear not broken.
Standard：ISO 4007, Propeller: 20 in

Figure 9 Crushed bump cap.
Standard: EN812, Propeller: 20 in

Figure 10 Propeller penetrating the helmet.
Standard: EN397, Propeller: 20 in

6 CONCLUSIONS

This study clarified the PPE types and situations in which they should be worn by drone users to ensure their safety by assessing the accident tendency and situation and the protective effects of PPE through NEISS case data and crash experiments. The following conclusions were obtained:

◊ Hand and eye lacerations and head injuries caused by drone or propeller collisions can be reduced by using protective gloves, eyewear with bands, and helmets that conform to existing standards.

◊ Wearing PPE during drone operation and repair can effectively reduce injuries.

◊ It is necessary to develop appropriate methods and standards to accurately evaluate and develop PPE for mitigating the risks associated with drone and propeller collisions.

ACKNOWLEDGMENTS

The results were obtained under a project (JPNP22002) commissioned by the New Energy and Industrial Technology Development Organization (NEDO). The authors would like to express their sincere gratitude to the NEDO.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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