DRONE BLADE INDUCED LACERATIONS: SKIN SURROGATE, INJURY THRESHOLD, AND TISSUE BIOMECHANICS

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Abstract

Drones have been increasing in popularity and are able to cause skin injuries ranging from minor abrasions to severe lacerations. The goal of this study was to evaluate different skin surrogates that can be used for drone safety testing, determine the aspects of drone blades that cause injuries, and to help manufacturers design safer drones by suggesting an injury threshold. Porcine skin, chamois, and fetal bovine skin were tested as potential tissue surrogates. Of these surrogates, fetal bovine skin best represented injuries observed in humans. The blade tip thickness, blade length, angular velocity, and blade tip speed of a variety of popular drones were measured. The injury caused by each drone blade contacting a fetal bovine skin surrogate at different speeds was recorded. Blade tip speed had the highest correlation to injury severity. Blade tip speeds above 25 m/s resulted in minor abrasions, and speeds above 60 m/s resulted in minor lacerations. To prevent severe injuries, drone manufacturers should design drones with blade tip speeds below the threshold of 60 m/s. To assess the effect of tissue thickness on drone laceration injuries, testing was also done on three different tissue thicknesses.

Introduction

As the use of drones becomes increasingly popular and more widespread, the number of drone related injuries is increasing. Drone accidents have caused a variety of injuries, including head injuries, open globe eye lacerations, and skin lacerations, which are the most common observed injury.[1, 2, 9]

Possible skin surrogates that can be used to test drone injuries include cadaver skin, porcine skin, chamois, and fetal bovine skin. Frozen cadaver skin has proven to be ineffective, due to ice crystal formation and rapid decay.[12] This limits cadaver skin from displaying realistic biomechanical properties. Human volunteers have been used; however, given extreme injury risk, this is not a viable option.[13] Porcine skin has been used in other experiments and has shown similar structure to human skin.[5, 10, 12, 16] Chamois, and other synthetic skin materials, have also been shown to represent qualities similar to human skin.[11, 14]

Another important aspect of skin surrogates used in drone testing is the tissue thickness. There are a range of different tissue thicknesses throughout the body, and the thickness may affect the severity of laceration injuries caused by drones. The average thickness of forehead tissue (skin and subcutaneous fat) is 3.6 mm, arm tissue is 5.37 mm, and thigh is 38.4 mm.[6-8]

The objectives of this study were first to compare the ability of skin surrogates to model drone blade laceration injuries, second to propose an injury threshold that can be used to design drones that reduce the risk of these injuries, and third to analyze the effect of tissue thickness on drone induced laceration injuries.

Materials and Methods

Testing system

A custom drone testing system was designed in Solidworks for the following experiments (Figure 1). The drone was mounted to the table, and the tissue surrogate was placed on a slide system to contact the drone blades. The sliding system moved the tissue surrogate at a constant measured speed and was adjusted to height of the drone blades for each specific drone tested. The skin was mounted on gelatin and held in place by hemostats.[11] A new skin sample was used for each test.

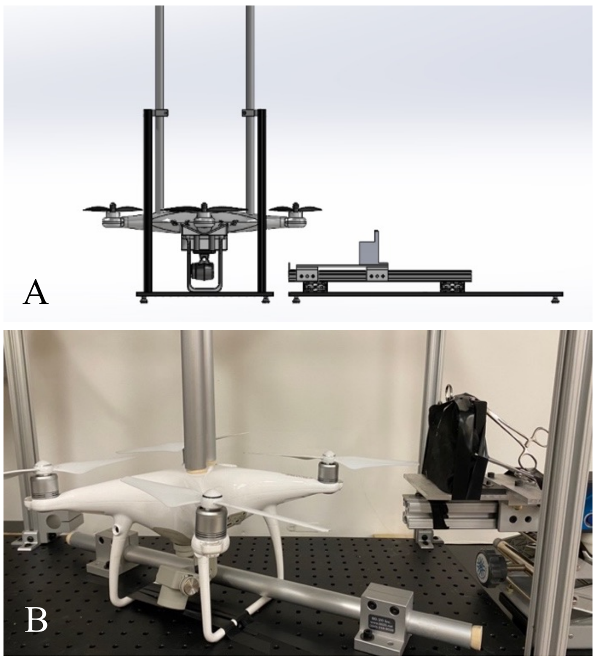

Figure 1: CAD design (A) and testing configuration with the fetal bovine skin (B).

Part 1: Skin surrogates

A total of 8 experiments were performed. Two drones were selected for testing: the Phantom 4 Advanced and the Air Hogs Axis 200. For the Phantom 4 Advanced, each surrogate type, chamois, porcine skin, and fetal bovine skin, was tested twice. For the Air Hogs Axis 200, the fetal bovine skin was tested twice. Angular velocity (rpm) was recorded using a laser tachometer. The observed injury caused by the drone was then assigned a level of injury severity: 0 for no injury, 1 for a minor abrasion, and 2 for a minor laceration. A minor laceration was defined as a cut through the epidermis.

Part 2: Drone parameters and proposed injury threshold

A total of 17 experiments were performed using nine different drones. The selected drones were the Phantom 4 Advanced (A), Air Hogs Axis 200 (B), Air Hogs Battle Tracker (C), Air Hogs 4T2010 (D), Star Wars X-Wing Fighter (E), Gyroscopes System (F), Syma FPV Real-Time (G), Holy Stone HS-Series (H), and Air Car A380 (I). For each drone, the blade tip thickness and blade length were measured, and angular velocity (rpm) was recorded using a laser tachometer. Blade tip speed was then calculated using the angular velocity and blade length. Each test used second trimester fetal bovine skin as the skin surrogate, due to its ability to accurately model drone blade laceration injuries in human skin.[12] The observed injury caused by the drone was then assigned a level of injury severity.

Part 3: Tissue thickness

Nine experiments were performed with the Phantom 4 drone. The skin surrogate, second trimester fetal bovine skin, was mounted to gelatin blocks of varying thicknesses. Three tissue thicknesses (combined thickness of skin and gelatin block) were selected: 3.6 mm, 21.0 mm, and 38.4 mm. These thicknesses were chosen to represent the range of tissue thicknesses across the human body. Three impact speeds were also selected: 0.5 m/s, 1.0 m/s, and 1.5 m/s. These lower speeds were chosen to avoid damage caused by the drone blades impacting and piercing the skin surrogate. The observed injury caused by the drone was assigned a level of injury severity.

Results

Part 1: Skin surrogates

The chamois and porcine skin surrogates displayed similar results when contacting the Phantom 4 blades. In tests 1 through 4, both surrogates had a minor abrasion with no laceration (Table 1). The fetal bovine skin had a laceration through the epidermis after it was impacted by the Phantom 4, but the fetal bovine skin had no visible damage after it was impacted by the Air Hogs Axis 200. The angular velocities for the Phantom 4 in tests 1 through 6 ranged from 7944 rpm to 8423 rpm while the Air Hogs Axis 200 had a significantly lower angular velocity of 2181 rpm.

Table 1: Test configuration and results for skin surrogate experiments.

Test	Drone	Surrogate	Angular velocity (rpm)	Observed Injury
1	Phantom 4	Chamois	7944	Minor abrasion
2	Phantom 4	Chamois	8209	Minor abrasion
3	Phantom 4	Porcine skin	8115	Minor abrasion
4	Phantom 4	Porcine skin	8209*	Minor abrasion
5	Phantom 4	Bovine skin	8209*	Minor laceration
6	Phantom 4	Bovine skin	8209*	Minor laceration
7	Air Hogs	Bovine skin	2181	No injury
8	Air Hogs	Bovine skin	2181*	No injury

*Average angular velocity taken from matched tests

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Part 2: Drone parameters and proposed injury threshold

Five of the 17 experiments resulted in no injury (Tables 2 and 3). Minor abrasions were observed in eight tests at blade tip speeds higher than 25 m/s. Minor lacerations were observed in four tests at blade tip speeds higher than 60 m/s. For example, the Air Car A380 caused no injury, minor abrasion, and minor laceration in three different tests depending on blade tip speeds ranging from 20.4 m/s to 31.7 m/s to 95.4 m/s accordingly (Figure 2).

Table 2: Test configuration and drone parameter measurements.

Test - Drone	Blade tip thickness (mm)	Blade length (mm)	Angular velocity (rpm)	Blade tip speed (m/s)
1-A	0.889	119.4	8115	101.4
2-B	0.508	64.0	2181	14.6
3-C	0.406	95.8	1526	15.3
4-D	0.406	78.2	3330	27.2
5-E	0.457	60.5	4605	29.1
6-F	0.533	97.0	2569	26.1
7-G	0.686	66.8	2719	19.0
8-G	0.686	66.8	5730	40.1
9-H	0.533	72.6	2971	22.6
10-H	0.533	72.6	6125	46.6
11-H	0.533	72.6	6072	46.2
12-I	0.381	27.4	7099	20.4
13-I	0.381	27.4	8658	24.9
14-I	0.381	27.4	11030	31.7
15-I	0.381	27.4	24960	71.7
16-I	0.381	27.4	30493	87.6
17-I	0.381	27.4	33226	95.4

Table 3: Results for the drone parameter experiments.

Test - Drone	Observed injury
1-A	Minor laceration
2-B	No injury
3-C	No injury
4-D	Minor abrasion
5-E	Minor abrasion
6-F	Minor abrasion
7-G	No injury
8-G	Minor abrasion
9-H	No injury
10-H	Minor abrasion
11-H	Minor abrasion
12-I	No injury
13-I	Minor abrasion
14-I	Minor abrasion
15-I	Minor laceration
16-I	Minor laceration
17-I	Minor laceration

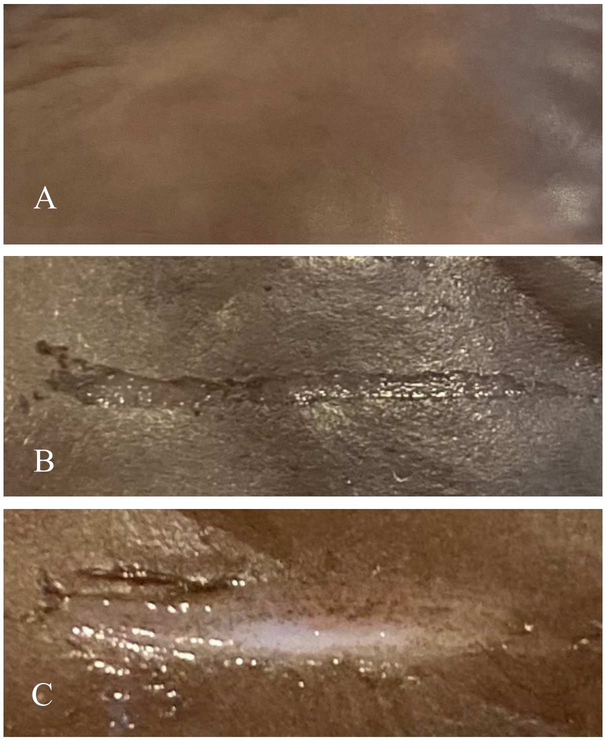

Figure 2: The fetal bovine skin surrogate showing no injury in test 12-I (A), a minor abrasion in test 14-I (B), and a minor laceration in test 17-I (C).

Overall, injury severity had the strongest correlation to blade tip speed (r^2=0.79). There was separation from no injury to minor abrasion at 25 m/s, and separation between minor abrasion and minor laceration at 60 m/s (Figure 3). However, injury severity did not correlate as strongly to angular velocity (r^2=0.56), which ranged from 1,526 rpm to 33,226 rpm. Blade length also did not correlate to injury severity (r^2=0.03), and ranged from 27.4 mm to 119.4 mm. Blade tip thickness correlated the least to injury severity (r^2=0.01), and ranged from 0.381mm to 0.889 mm.

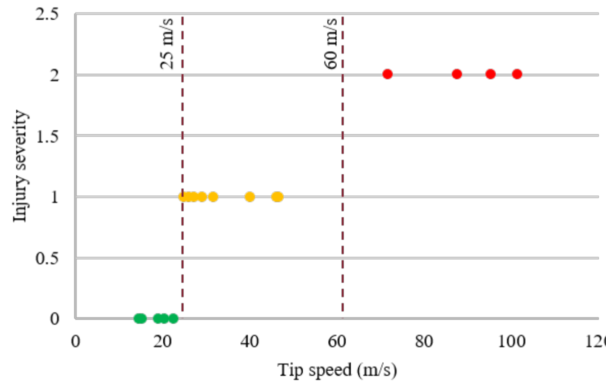

Figure 3: Injury severity vs tip speed for all tests with proposed injury thresholds. Green represents no injury, yellow represents minor abrasions, and red represents minor lacerations.

<u>Part 3: Tissue thickness</u>

Similar results were observed for each of the three tissue thicknesses. There was a minor laceration for each impact test regardless of tissue thickness or impact speed (Table 4). When impacting the Phantom 4 blades, the tests with the thinnest tissue thickness and thickest tissue thickness both obtained a minor laceration (Figure 4).

Table 4: Test configuration and results for tissue thickness experiments.

Test	Tissue thickness (mm)	Target impact speed (m/s)	Observed injury
1	3.6	0.5	Minor laceration
2	3.6	1.0	Minor laceration
3	3.6	1.5	Minor laceration
4	21.0	0.5	Minor laceration
5	21.0	1.0	Minor laceration
6	21.0	1.5	Minor laceration
7	38.4	0.5	Minor laceration
8	38.4	1.0	Minor laceration
9	38.4	1.5	Minor laceration

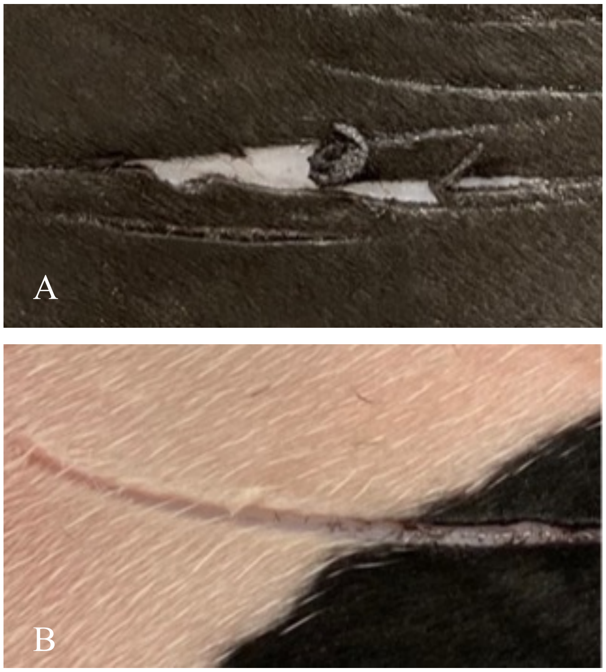

Figure 4: A minor laceration on 3.6 mm tissue resulting from a 1.5 m/s impact in test 3 (A), and a minor laceration on 38.4 mm tissue resulting from a 1.5 m/s impact in test 9 (B).

Discussion

The chamois and 6 month-old porcine skin did not prove to be viable skin surrogates. The Phantom 4 Advanced drone has caused severe skin lacerations in humans, and the porcine skin and chamois did not replicate this. In contrast, the fetal bovine skin proved to be an effective skin surrogate. The lacerations caused by the Phantom 4 and the inability of the Air Hogs Axis 200 to cause skin related injuries are consistent with recorded cases in humans.

Blade tip speed proved to correlate the most to laceration injuries caused by drone blades, with speeds above 25 m/s causing minor abrasions and speeds above 60 m/s causing minor lacerations. In order to avoid severe injuries caused by drone propellers, maximum blade tip speed should stay below the threshold of 60 m/s, especially for drones designed for toy use. Interestingly, all other parameters (blade tip thickness, blade length, and blade angular velocity) were not correlated to risk of skin injury. This implies that manufacturers can create drones with many different blade designs as long as they evaluate blade tip speed as the injury criteria.

The nine different drones were selected to represent a broad range of commercial and toy drones that are most likely to be handled and flown in close proximity to people. Seven of the nine drone types produced injury with a range of blade designs. The two drones that did not result in injury were tested at their maximum speed. The minor abrasions represented damage to the epidermis while the minor lacerations included damage through the epidermis to the underlying dermis skin layer.

Tissue thickness did not influence the severity of injuries caused by the Phantom 4 drone. The tests with skin surrogates representing forehead tissue thickness experienced the same injuries as the tests with skin surrogates representing thigh tissue thickness.

There are two limitations of this study. First, the skin surrogate is not living human skin. While previous researchers utilized human volunteer testing, the unknown severity prevented this option.[11, 13] Second, there are countless drone blade configurations and further testing could provide additional insight into their safe design. Overall, while there exist many injury metrics for evaluating brain injury from drone impacts, this is the first injury threshold proposed for drone blade induced skin lacerations.[3, 4, 15]

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