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A Comprehensive Experimental Study on Head Trauma in a 3-Year-Old Child Due to Unmanned Aerial Vehicle Collisions

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Abstract

Purpose: This research aimed to evaluate the biomechanical impact on a 3-year-old child's head during collisions with unmanned aerial vehicles (UAVs), focusing on the effects of UAV mass, impact velocity, and impact direction, using the Head Injury Criterion (HIC) for assessment.

Methods: Experiments simulated impacts with UAVs of varying masses (249g, 500g, 900g) and velocities (19.0, 24.0, 29.0 m/s) from different directions. HIC values were measured for each scenario and analyzed in relation to the Abbreviated Injury Scale to determine potential injury severity.

Results: The findings showed that both the UAV's mass and impact velocity have a significant influence on the HIC value, with higher figures indicating a greater risk of serious injury. For the UAVs weighing 249 g and 500 g, frontal impacts resulted in the highest HIC values; however, for the UAV weighing 900 g, the highest HIC value occurred for the back hit. Moreover, injury risk was found to escalate non-linearly with increased velocity, especially for heavier UAVs.

Conclusions: The study emphasizes the critical influence of UAV mass and impact velocity on the severity of head injuries in children. Increased mass and velocity correlated with higher HIC values, indicating a greater likelihood of severe injury. Frontal impacts were particularly hazardous for lighter UAVs, while rear impacts were more dangerous for heavier UAVs. These findings support the need for stringent regulations on UAV operational parameters, focusing on speed and mass limitations, to mitigate the risk of severe head injuries in children.

Keywords

Unmanned Aircraft Vehicles, UAV threat, collisions with humans, HIC, head trauma

1. Introduction

Unmanned aerial vehicles (UAVs, drones) are technical solutions that are commonly used nowadays for a wide range of civilian and military applications. The main reasons contributing to the high interest in drones are the UAV's advantages, related to its ability to wirelessly record various types of data (image, sound, temperature, etc.) and transport a range of payloads, from commercial goods to sensitive materials, including explosives. The widespread use of UAVs is also influenced by the high availability of the equipment, resulting from the extensive offer of manufacturers, who launch UAVs with various parameters (dimensions, weight, speed, range, etc.), equipped with a variety of accessories (cameras, microphones, sensors, etc.) [2,19,20].

With increased UAV utilization, new safety risks have arisen, particularly those affecting human health and safety. The principal threat to humans is the risk of being hit by a UAV, which can end in injuries. The threat of collision with a drone also involves birds as well as other flying objects [6]. The issue of collision injuries is very well recognised for vehicle collisions, taking into account injuries to people inside the vehicle as well as pedestrians. Research from this area provides important knowledge to establish the survey methodology for UAV impact [10,17,23,34].

Injury severity is influenced by incident specifics—such as UAV speed and mass, impact angle, location of the UAV's contact with the human body, and the impacted individual's body structure and age. Among those exposed to the most serious effects of impact are children, due to their early stage of development of body systems, such as the skeletal system. Particularly dangerous are blows to the head, leading to serious injuries such concussion and, in extreme cases, even death [18].

The main purpose of the article was to present and discuss the results of an experimental investigation focused on identifying biomechanical phenomena in a 3-year-old child occurring during an impact to the head by an unmanned aerial vehicle. The study considered various UAV weights, velocities, and selected collision trajectories, including horizontal impact from the front, from the back and from the side of the head. The severity of injury during impact was determined by determining the Head Injury Criterion (HIC) and correlating the results obtained with the Abbreviated Injury Scale (AIS). The study also analyzed the acceleration duration associated with each impact. The research was carried out using the author's research methodology, which included the use of the author's test stand and the author's UAV model.

2. Materials and methods

2.1. Injury Assessment Methodology

Identification of injuries occurring in a 3-year-old following an impact to the head with an unmanned aerial vehicle were performed based on the research methodology of determining negative health consequences based on the determination of the HIC value during impact, which was compared with the AIS scale. The HIC is a measure of the likelihood of head injury arising from an impact, which correlates with the AIS, especially for head injuries. While AIS addresses the anatomical and clinical severity of injuries, HIC quantifies the physical parameters of an impact, such as acceleration and duration of force. Together, AIS and HIC are instrumental in vehicle safety assessments and the design of protective systems, as they provide a comprehensive view of both the biomechanical forces involved in accidents and the potential for injury severity [33]. The other criteria for head trauma include the Brain Injury Criteria (BrIC), which is focused on brain injury. The BrIC value is also compared with the AIS scale to determine the level of severity [8].

The Head Injury Criterion is a pivotal metric for evaluating the risk of head injury in the event of a vehicular impact. It quantifies the potential for brain injury by integrating the resultant acceleration of the head, as measured at the head's center of gravity over a defined time window. HIC emphasizes the impact of linear accelerations on head trauma, discounting rotational forces [7,11]. In practice, the HIC value is derived over a 15 or 36 millisecond period, respectively known as HIC15 and HIC36, to gauge the intensity and duration of head acceleration during a crash [4,22]. The 36 ms window specifically addresses impact waveforms extending beyond this duration. The calculation involves selecting the time interval within these windows where the HIC value peaks, optimizing for the initial (t_1) and final (t_2) instants of this period [15], according to formula (1):

$$HIC_{t_1,t_2} = max\left\{(t_2 - t_1) * \left[\left(\frac{1}{t_2 - t_1}\right) * \int_{t_1}^{t_2} a(t)dt\right]^{2,5}\right\} \qquad (1)$$

where:

t_1 – is the initial time instant marking the beginning of the interval,

t_2 – is the final time instant marking the end of the interval,

a(t) – is acceleration as a function of time, experienced by the head during the impact.

Despite being a robust indicator of the severity of head injuries, correlating higher HIC values with increased injury levels, HIC does not provide a direct interpretation of injury. It serves as an index that, through additional mappings to the Abbreviated Injury Scale, allows for the assessment of injury severity, from minor to critical [27]. The AIS is a globally recognized severity scoring system that classifies injuries on a scale from one (minor) to six (maximal, unsurvivable injury), based on their threat to life. It forms the backbone of the Injury Severity Score (ISS), which aggregates injuries from different body regions to assess overall trauma severity [5]. The scale is periodically updated to reflect advancements in medical understanding and trauma care systems, with significant implications for assessing injury impacts and healthcare outcomes [9]. The AIS, a severity scoring system, is utilized alongside HIC to provide a comprehensive injury assessment, rating injuries from minor (1) to maximal (6). The relationship between HIC and AIS is such that as HIC values increase, so does the AIS level, indicating a more severe injury. At the critical HIC threshold of 900 for a 3-year-old, injuries may include serious conditions like unconsciousness or depressed skull fractures, which fall under an AIS3+ level. This threshold is carefully determined, considering the physiological differences between a child's and an adult's head, where a child's head shows different tolerances and thus requires adjusted safety measures [21]. The correlations between the HIC value and the AIS scale are indicated in Table 1.

Table 1. HIC, AIS code and head injury [32]

HIC value Adult	HIC value Child 3 YO	AIS code	Injury Level	Head injury	Fatality Range
< 134	< 121	0	No injury	No injury	0.0 %
135 – 519	122 – 467	1	Minor	Headache or dizziness	0.0 – 0.1%
520 – 899	468 – 809	2	Moderate	Unconscious less than 1 h; linear fracture	0.1 – 0.4%
900 – 1254	900 – 1129	3	Serious	Unconscious 1 – 6 h; depressed fracture	0.8 – 2.1%
1255 – 1574	1130 – 1417	4	Severe	Unconscious 6 – 24 h; open fracture	7.9 – 10.6%
1575 – 1859	1418 – 1673	5	Critical	Unconscious more than 24 h; large hematoma	53.1 – 58.4%
> 1860	> 1674	6	Maximum	Non-survivable	Virtually unsurvivable

The scaling of the HIC values between adults and a 3-year-old child acknowledges the significant biomechanical differences in their skulls. A 3-year-old's skull is characterized by cranial sutures, which are more flexible and allow for greater deformation and energy absorption upon impact. This flexibility results in a different response to force compared to the more rigid, fused skull of an adult. Consequently, the HIC threshold for a 3-year-old is scaled down to reflect this increased capacity for energy absorption and deformation. For instance, the HIC threshold for serious injury (AIS 3+) for an adult is set at 900, while for a 3-year-old, it is adjusted to 810. This adjustment is based on the understanding that a child's skull can absorb more impact due to the properties of the cranial sutures, leading to a different distribution and absorption of force [13].

2.2. UAV model and test stand

The unmanned aerial vehicle with which the impacts were realized was a proprietary composite drone. The drone model (Fig. 1) was made of T300 multidirectional carbon fiber (Toray Composite Materials America, Inc) and epoxy resin to form a composite using the infusion method, resulting in durability to allow a number of measurements with a single device. The reference model for the geometry of the drone made for the tests was the Phantom 2, from manufacturer DJI, which was mapped at a smaller scale. The dimensions of the fabricated drone were 30 cm x 30 cm, and its basic weight was equal to 249 g. The design of the drone made it possible to gradually increase the weight for subsequent measurement series.

Figure 1. Drone model use in research

For the performance of the measurements, it was necessary to prepare a test stand, which was the launcher with which the UAV was launched. The surveys were performed using the author's launcher, with which the UAV was launched head-on. The stand consisted of a trolley mounted on a profile. Elastic rubbers were connected to one end of the profile, used to pull the trolley with the drone on it. Once the rubbers were stretched to the appropriate level, the trolley was released, throwing the drone towards the head located at the end of the profile. A shock absorber was mounted at the end of the profile to brake the trolley and prevent it from being damaged when hitting the end of the profile.

Tests were conducted on a dedicated stand, designed for the experiment. Its’ greatest part is based upon a 6 meter steel square profile with 80 millimeter side. Transverse legs were welded near the ends of the profile and mounted with adjustable plates to compensate for variations of terrain height. One end of the stand has a spring damper with a force sensor. It ensures a longer lifetime of the carriage, which experiences great loading during each impact. Profile is used as a rail for the carriage with drone mounting. Drone is supported from its back and bottom by replaceable MDF blocks, ensuring stability and proper orientation during acceleration. Lower part of the carriage is 3D printed from PLA and equipped with 6 bearings in total. They support the whole carriage structure, ensuring locking in 5 degrees of motion - leaving space for linear movement along the profile only. Since the whole carriage structure experiences great loads during impact, all of its parts are replacable if damaged. Front end of the stand has elastic ropes attached to it. They are used as a sling to accelerate the carriage. The further carriage is moved with the rope, the higher tension and greater velocity during the impact. Positioning of the carriage at the same distance from the front of the stand results in similar impact velocities. Carriage collides with the damper and drone is freely released and shortly after hits Q3 head.

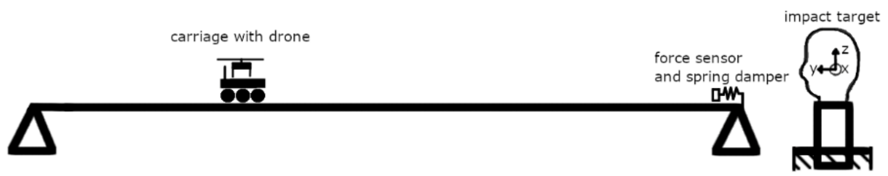


Figure 2. Test stand

A dummy head of a 3-year-old child, manufactured by Humanetics Innovative Solutions, Inc. model Q3, was used for the research. The model consisted of combined modules of the head (designation 020-1100) and articulated neck (designation 020-2100). The head used reflects the biomechanical, kinematic and anthropometric behavior of a 3-year-old child, as certified by Humanetics' laboratory for dynamic properties. At the center of gravity of the head is a set of 3 uniaxial piezoelectric accelerometers Endevco 7264C, compliant with SAE standards, provided for impact and anthropometric tests. The maximum range of the sensors is ±2000 g. The set of 3 sensors was placed at the center of gravity of the head, using a rigid interface. The acceleration value read from the head is the modulus of total acceleration, which is the vector sum of the values measured by each accelerometer. The use of only the head dummy in the study was due to the adopted purpose, focused on determining the injuries to the child's head during the UAV impact, without considering the injuries transmitted to other parts of the body.

All the drone's impacts on the dummy's head were recorded using NAC IMAGE TECHNOLOGY's high-speed camera, model MEMRECAM HX-3. The camera is equipped with a fixed-focus 35mm lens. The camera allows accurate analysis of high-speed phenomena, impossible for the human eye and conventional cameras. During the survey, images were recorded at 4,500 frames per second, at a standard resolution of 1920x1080 pixels. The segment preceding the impact of the dummy's head to the moment after the impact occurred was recorded from each test. Markers were applied to the head, allowing the use of tracking software and additional accurate determination of movement parameters during the trials - position and velocity, as well as validation of accelerometer readings.

2.3. Experimental conditions and data analysis

The research program assumed the implementation of a series of measurements, considering the performance of strikes to the head from 3 directions: from the front, from behind and from the side. For each direction considered, 3 UAV weights were considered: 249 g, 500 g and 900 g. Tests were conducted while inflicting different impact velocities, which made it possible to determine approximate velocity thresholds at which the determined HIC value indicated the occurrence of serious head injuries. Three variants of impact velocity were considered during testing: low (19.0 ± 0.5 m/s), medium (24.0 ± 0.5 m/s), and high (29.0 ± 0.5 m/s).

For each conditions variant, 20 impacts were carried out, from which the HIC was determined. The results of the HIC values were compared with the AIS scale, based on which the effects of injury were determined for each impact variant. In order to reliably determine the biomechanical phenomena occurring in the head of a 3-year-old during a UAV impact, an analysis of the trajectory of acceleration as a function of time was also performed. This was to investigate how long the head is exposed to high acceleration values, implying more severe health consequences.

The weights (249 g, 500 g, and 900 g) and impact speeds (low, medium, high) were selected to represent a range of realistic scenarios involving UAV collisions. The chosen weights cover a spectrum of commonly used UAVs (249 g - DJI Mini 3 Pro; 500 g - Yuneec Mantis Q; 900 g - DJI Mavic 3), from lightweight consumer drones to heavier models. The impact speeds were determined based on preliminary measurements and are intended to simulate different collision intensities that a UAV might experience, from a slow impact to a high-speed collision. This range allows for a comprehensive analysis of the potential risks and injury outcomes associated with different UAV weights and velocities.

The measurement conditions in the study did not encompass impacts on the top of the head, a decision informed by extensive literature review [3,14,24,25] indicating that such impacts, while recognized, are infrequent and typically do not result in high HIC values given the usual impact velocities and UAV weights. Moreover, the scenario would require considering substantial drone heights and the potential failure of mechanisms designed to mitigate free fall, factors that are not central to the majority of UAV collision circumstances.

3. Results

Figures 4 and 5 illustrate a summary of the results of the determined HIC value as a function of impact velocity, UAV weight and impact direction.

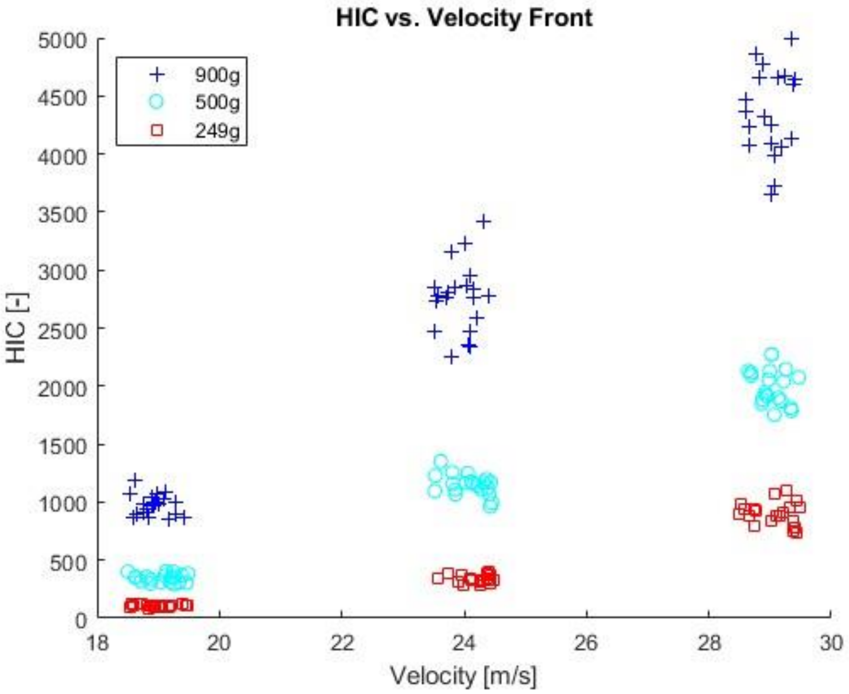


Figure 4. Overview of HIC results for UAV weight = 249 g

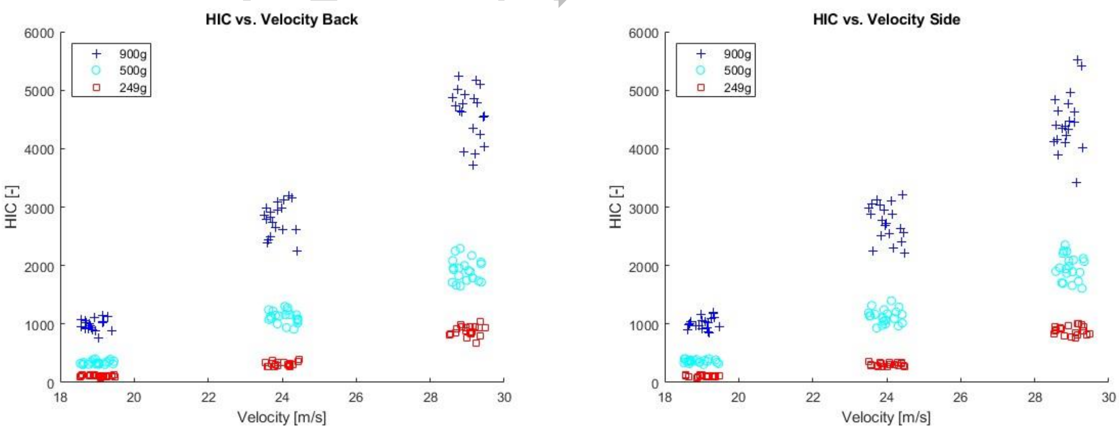


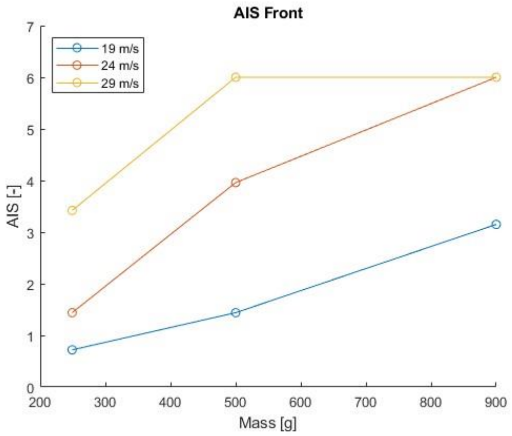
Figure 5. Overview of HIC results for UAV weight = 500 g (on left) and UAV weight = 900 g (on right)

Table 2 contains the averaged results of the surveys and a reference to the AIS level resulting from the determined HIC value.

Table 2. Mean HIC scores and AIS levels

Direction	UAV 249 g			UAV 500 g			UAV 900 g		
	Mean velocity [m/s]	**HIC**	**AIS**	**Mean velocity [m/s]**	**HIC**	**AIS**	**Mean velocity [m/s]**	**HIC**	**AIS**
Front	19,0	109,5	<1	19,0	346,9	1	18,9	974,5	3
	24,2	336,7	1	24,1	1147,7	4	23,9	2762,9	6
	29,1	901,9	3	29,0	1997,9	6	29,0	4359,1	6
Back	19,1	111,3	<1	19,0	337,9	1	18,9	986,8	3
	24,0	315,1	1	24,1	1122,0	3	23,9	2797,4	6
	29,0	881,0	3	28,9	1918,7	6	29,1	4599,1	6
Side	19,1	110,4	<1	18,9	362,9	1	19,0	1009,4	3
	24,0	310,8	1	24,0	1131,1	4	24,0	2738,5	6
	29,0	887,2	3	28,9	1962,8	6	28,9	4454,5	6

Figure 6 illustrates the correlation between impact velocity, weight and AIS level of damage, as derived from the measurements, for each UAV impact direction.



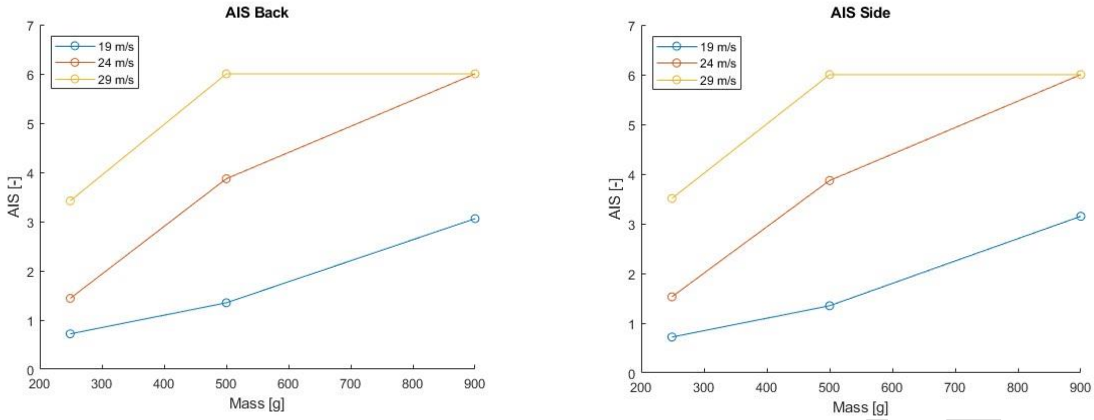


Figure 6. AIS level for each impact scenario

Figure 7 presents sample waveform of acceleration as a function of time, representative of the different measurement scenarios.

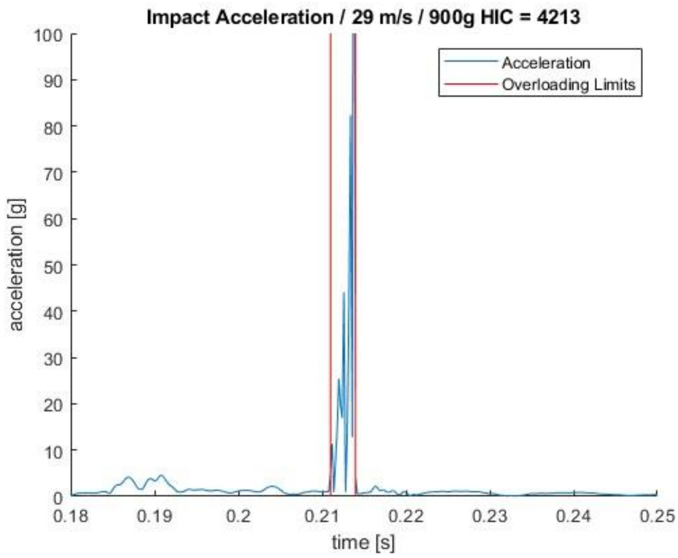


Figure 7. Representative waveforms of acceleration for UAV weight = 900 g

Table 3 presents the mean impact energy during collisions for different UAV weights, velocities, and impact directions, along with the corresponding AIS levels.

Table 3. Mean impact energy during collisions

Direction	UAV 249 g			UAV 500 g			UAV 900 g		
	Mean velocity [m/s]	Impact Energy [J]	AIS	Mean velocity [m/s]	Impact Energy [J]	AIS	Mean velocity [m/s]	Impact Energy [J]	AIS
Front	19,0	44.9	<1	19,0	90.6	1	18,9	160.7	3
	24,2	72.9	1	24,1	145.2	4	23,9	257.0	6
	29,1	105.4	3	29,0	210.3	6	29,0	378.5	6
Back	19,1	45.4	<1	19,0	90.3	1	18,9	160.7	3
	24,0	71.7	1	24,1	145.2	3	23,9	257.0	6
	29,0	104.7	3	28,9	208.8	6	29,1	381.1	6
Side	19,1	45.4	<1	18,9	89.3	1	19,0	162.5	3
	24,0	71.7	1	24,0	144	4	24,0	259.2	6
	29,0	104.7	3	28,9	208.8	6	28,9	375.8	6

4. Disscussion

In the study examining UAV – head collisions, the data indicates a distinct relationship between UAV mass, impact velocity, and resulting trauma severity. For UAVs weighing 249 grams, frontal collisions at a velocity of 19.0 m/s are associated with HIC scores of 109.5, suggesting a minimal risk of head injury (AIS <1). With an increase in impact velocity to 24.2 m/s, the HIC value rises sharply to 336.7, corresponding to a mild injury risk (AIS 1). A further increase in velocity to 29.1 m/s results in a HIC value of 901.9, indicative of a serious risk level (AIS 3). In scenarios involving rear and side impacts at the same UAV weight, the HIC values remain comparably low at the lower velocity of approximately 19.0 m/s, suggesting a minimal injury risk. However, as the velocity increases to around 29.0 m/s, there is a substantial increase in HIC scores to values such as 881.0 for back and 887.2 for side impacts, with corresponding AIS values reaching 3, suggesting a transition from negligible to moderate injury risk.

For unmanned aerial vehicles (UAVs) weighing 500 grams, even at the lower impact velocity of 19.0 meters per second (m/s), frontal collisions result in Head Injury Criterion (HIC) scores of 346.9, signifying a minimal yet definitive injury risk with an Abbreviated Injury Scale (AIS) rating of 1. As the impact velocity is elevated to 24.1 m/s, the HIC value soars to 1147.7, which is indicative of a serious injury potential with an AIS level of 4. At the highest tested velocity of 29.0 m/s, the HIC score escalates dramatically to 1997.9, correlating with the most severe injury rating on the AIS scale at level 6. The pattern of increasing HIC values with velocity is consistent across rear and side impacts for this UAV weight class, demonstrating a low to moderate injury risk at lower velocities, and a significant leap to high severity at increased velocities.

In the case of 900-gram UAVs, results highlight a significant hazard of head trauma from impacts at even lower speeds. Frontal impacts at 18.9 m/s resulted in a HIC of 974.5, while rear and side impacts produced HIC values of 986.8 and 1009.4, respectively, each associated with an AIS indicative of serious injury risk. As impact velocity increased modestly to 23.9 m/s, the HIC measurements rose sharply: frontal impacts recorded a HIC of 2762.9, rear impacts showed 2797.4, and side impacts were at 2738.5. Upon reaching impact velocities of 29.0/29.1 m/s, the HIC values reached their zenith, with the apex being a HIC of 4599.1, in each instance suggesting the highest level of injury severity as per the AIS scale.

The impact energy values for individual impacts indicate that the maximum energy value for the UAV of 249 g, at 105 J, occurred for impacts at about 29 m/s, for AIS3 level. For a UAV weight of 500 g for speeds of about 19 m/s the energy was around 90 J, for speeds of about 24 m/s it reached around 145 J, at AIS3+ level. For speeds of 29 m/s it exceeded 205 J, indicating AIS6. Impacts of a UAV weighing 900 g at 19 m/s showed impact energies above 160 J, indicating AIS3 level. Impacts at speeds around 24 m/s and 29 m/s translated into impact energies above 250 J and 370 J, respectively, indicating AIS6. The impact energy and AIS scale relationships determined in the study are consistent with the literature [26], where it was indicated that impact energy >90 J indicates an AIS3+ level.

Study [14] employed both simulation and experimental approaches to understand the injury potential from drones of varying weights and from different fall heights. The results of Koh et al.'s research indicated that not only the weight of the UAV but also the height from which it falls significantly affects the injury level as classified by HIC and AIS values. For instance, the injury outcomes from a UAV weighing 0.305 kg falling from 60.96 m were comparable to those from heavier UAVs falling from lesser heights, highlighting the complex interplay between UAV mass and fall dynamics. Drawing parallels, the current article extends the scope of investigation to include the effects of UAV collisions from a horizontal perspective (i.e., impacts to the side, rear, and front of the head) and considers the impact velocity as a critical factor. Both studies underscore the risk severity through HIC values, with the current research further emphasizing how increased velocities amplify the risk of injury across various UAV weights. The most significant connection between the two pieces lies in their mutual emphasis on the quantitative relationship between UAV characteristics (weight and velocity or height) and the risk of head injury. Koh et al.'s findings serve as a foundational reference point that complements the current article's insights into the risks associated with UAVs in motion, reinforcing the broader understanding of the biomechanical phenomena involved in UAV-related accidents. Both pieces contribute valuable data towards developing safety standards and regulations for UAV operations to minimize the risk of head injuries to individuals.

In the realm of biomechanical research, the investigation into head and neck injuries caused by UAV impacts has progressed significantly since the experiments described in [3]. The previous studies, utilizing a Hybrid III dummy head and neck fitted with sensors, set a precedent for assessing the impact of UAVs of varying masses, ranging from 1.2 kg to 11 kg, on potential head injuries as quantified by the HIC and Neck Injury Criteria (Nij), juxtaposed against the AIS. The experiments by Campolettano et al. demonstrated that the orientation of the UAV's center of mass during impact greatly influences the severity of head injuries. This was evidenced by varied HIC readings in scenarios where the drone made frontal contact with different parts of the head. For example, an impact on the face's center by a DJI Phantom 3 drone resulted in a peak acceleration of 72 g, whereas an oblique impact involving the drone's leg turned out to be less severe, indicating the influence of impact angle and contact area on the injury severity. In line with these findings, contemporary research has further dissected the relationship between UAV weight, collision velocity, and trauma severity, providing a comprehensive view across various UAV masses. It was found that lighter UAVs (e.g., 249 grams) could lead to minimal risk of injury at lower velocities (HIC score of 109.5 at 19.0 m/s). However, as impact speeds increase, the risk escalates significantly, with serious injuries (AIS level 3) corresponding to much higher HIC scores. When contrasting these findings with the impact of heavier UAVs, a stark difference is observed. UAVs weighing 500 grams already present a definitive injury risk (AIS level 1) at lower velocities, with HIC values soaring to critical levels (AIS level 6) as velocities reach 29.0 m/s. For UAVs at the upper end of the weight spectrum (900 grams), the danger of head trauma is accentuated even at lower speeds, with HIC values exceeding 900 from impacts at velocities as low as 18.9 m/s. These current investigations extend the initial research by [3] substantiating the correlation between increasing UAV mass and velocity with the severity of injury. Furthermore, it underscores the critical nature of secondary injury mechanisms, such as lacerations or impalements from drone components, which were highlighted in earlier studies as noteworthy contributors to the overall injury risk.

The scientific discourse emanating from the research in [25] presents a comparative analysis of head injuries resulting from collisions with a DJI Phantom III drone, using a Hybrid III crash test dummy and human body models validated in the MADYMO simulation package. The simulations, incorporating nine impact variants, considered variations in three selected parameters: impact velocity (ranging from 0 m/s to 18 m/s, with increments of 2 m/s), impact elevation (horizontal at 0˚, angled at 45˚, and vertical fall at 90˚), and impact direction (front at 0˚, side at 90˚, and rear at 180˚). The severity of head injuries was evaluated using the HIC. The findings of these simulations elucidate that the kinetic energy—and by extension, the severity of potential head injuries—as indicated by HIC values, escalates with the drone's impact velocity. Notably, horizontal impacts were associated with significantly higher HIC values than angled and vertical impacts, the latter presenting the lowest HIC values. The direction of the impact was also found to minutely alter the HIC values. A comparative assessment of the Hybrid III dummy and human body models revealed that the dummy underestimates head injury severity in the angled (45˚) and vertical (90˚) impact scenarios, producing lower HIC scores than those obtained from the human body simulations. This discrepancy in head injury outcomes between the two models is attributable to differences in the neck complex, which influences the acceleration of the head upon impact. In juxtaposition with the article in question, which investigates the biomechanical phenomena occurring in a 3-year-old child's head upon UAV impact, a common thread in both studies is the emphasis on the HIC as a pivotal measure of head injury severity. The article extends the scope of the UAV impact study to encompass a wider range of UAV weights and velocities, as well as the acceleration duration during each impact. It also leverages a unique research methodology, including a proprietary test stand and UAV model.

Paper [24] focused on a narrower range of UAV speeds and varied the angle of impact, examining inclinations of 90˚, 58˚/65˚, and 0˚. Their findings indicated that impacts at a 90˚ angle with a speed of 9.9 m/s yielded a HIC of 14.0, while the same angle at a speed of 15.1 m/s resulted in a HIC of 63.3. Notably, a more oblique impact at 58˚ with a speed of 14 m/s produced a higher HIC of 132.1, and the simulation suggested that horizontal drone collisions at speeds exceeding 14 m/s could result in HIC values over 700, denoting a high probability of serious head injuries. In contrast, the article under discussion considers a broader spectrum of UAV weights and velocities while measuring the HIC and the AIS. The investigation reveals that even at lower velocities, a UAV weighing 900 grams can lead to HIC scores indicative of serious injury risk. For instance, a frontal impact at 18.9 m/s resulted in a HIC of 974.5, significantly higher than any of the values reported in [24].

Study [30] presented results from eight tests involving UAVs with masses under 2 kg, encompassing a range of five drones that included three multirotor quadcopters and two fixedwing planes with masses ranging from 250 g to 1300 g. These UAVs were either dropped vertically onto a Hybrid III crash test dummy from a height of 40 m or collided at a 58-degree angle. Their findings highlighted that a drone weighing 650 g impacting at a velocity of 19.07 m/s yielded the highest injury level (HIC = 413). Other variations demonstrated a lower injury level (HIC < 50), attributed to lower impact velocities, UAV mass, and energy dispersion during contact. Conversely, the article in question discusses UAV weights and velocities with a narrower focus, specifically on the effects of frontal, rear, and side impacts on a 3-year-old child's head. The UAV weights examined were 249 g, 500 g, and 900 g. For the 249 g UAV, the study delineates a clear trend where an increase in impact velocity from 19.0 m/s to 29.1 m/s results in a marked escalation of HIC values from 109.5 to 901.9, indicating a progression from minimal to serious injury risk. The study further indicates that for the 500 g UAV, even a lower impact velocity leads to a HIC of 346.9, which increases significantly with velocity, denoting a higher risk of severe injury. For the heaviest UAV at 900 g, the study presents a stark increase in injury risk even at lower speeds, with substantial rises in HIC values across all tested velocities, suggesting severe injury potential.

The experimental research in [29] provided valuable insights into the biomechanical implications of UAV collisions with human surrogates. Their utilization of Post Mortem Human Surrogates (PMHS) allowed for the exploration of injury outcomes across a spectrum of impact angles and velocities, employing diverse UAV models such as the DJI Phantom 3, DJI Mavic Pro, DJI Inspire 2, Sensefly eBee+, and one from Vendor 1. Study [28]reported their most critical injury with a HIC value of 5473 from a frontal collision at a 58° angle and a velocity of 21.5 m/s, resulting in an AIS severity level of 2 with a high probability of skull fracture. The experimental configuration of the current study diverges from [29] in the context of surrogate model biofidelity. Whereas [29] employed PMHS, known for their anatomical and mechanical resemblance to the human body post-mortem, the current study's surrogate is modeled after a living child's head, introducing different biomechanical response characteristics. Such differences are instrumental in interpreting the disparities in HIC values and injury severity scales observed between the two studies. For instance, the highest HIC value observed in the current study is 4599.1, a notable difference when compared to the HIC of 5473 reported in [29]. This discrepancy underscores the critical role that surrogate model selection plays in impact studies, influencing injury prediction and risk assessment. Moreover, the current study's detailed analysis of the acceleration duration associated with each impact, UAV mass, and velocity relationships to injury risk, enriches the understanding of UAV collision dynamics. It expands the conversation on UAV safety and head trauma, offering a juxtaposition of UAV impact studies that employ different surrogate models, and thus, providing a broader foundation for future UAV regulations and safety standards.

The incident documented in [1] illustrates a significant safety concern, with a UAV pilot sustaining deep lacerations and underlying bone fractures to the fingers due to propeller contact during landing maneuvers. This case underscores the biomechanical hazards posed by the rapidly rotating blades of UAVs, which have the potential to inflict severe injuries such as abrasions, cuts, fractures, and even amputations. Study [12] expand upon this issue through a comprehensive review of drone-related injuries among children, detailing incidents arising from attempts to retrieve stalled UAVs or catch them while flying. The types of injuries cataloged in their review ranged from hand lacerations to eye injuries, concussions, and various fractures, reinforcing the diverse nature of trauma that can be inflicted by UAVs in different scenarios. Further emphasizing the risk to ocular health, Paper [28] presented two cases of eye injuries due to UAV propellers. In one instance, a 9-year-old boy suffered injuries to the eyelid, cornea, ear, nasal bridge, and neck, with the corneal injury resulting in a significant reduction in visual acuity. Another case involved a 21-month-old girl who sustained partial conjunctival laceration and corneal abrasions from a toy drone, which required surgical intervention. Similarly, study [16] reported on a 9-year-old child who experienced lacerations near the eye, ear, nasal bridge, and neck after being struck in the face by a drone propeller. Although the prescribed treatment facilitated recovery, the child suffered permanent visual field deficits, highlighting the long-term consequences that can arise from UAV-related accidents.

Improving protection against the possibility of a severe head injury is provided by implementing technologies in UAVs that minimise the risk of impact, such as anti-approach systems. Other possible solutions are personal protective equipment such as helmets [31].

5. Conclusions

The paper was devoted to the problem of biomechanical phenomena in the head of a 3-year-old child occurring during impact with an unmanned aerial vehicle. The main aim of the paper was to present and analyse data from experimental research, carried out on the basis of the author's research method. The method involved the determination of the HIC value occurring during impacts to the head of UAVs with different masses (249 g, 500 g, 900 g), from different directions (front, back, side) and with different impact velocities (19.0 ± 0.5 m/s, 24.0 ± 0.5 m/s, 29.0 ± 0.5 m/s). The HIC value, was then compared with the AIS scale to determine the severity of injury. Analysis of the collected results led to the following conclusions:

The severity of head injuries sustained from UAV impacts is significantly influenced by both the mass of the UAV and the velocity at which the impact occurs. As expected, higher mass and velocity correlate with increased HIC values, indicating a greater risk of serious injury. The severity of head injuries sustained from UAV impacts is significantly influenced by both the mass of the UAV and the velocity at which the impact occurs. As expected, higher mass and velocity correlate with increased HIC values, indicating a greater risk of serious injury.

Frontal impacts consistently resulted in higher HIC values across all UAV masses and velocities when compared to rear and side impacts, highlighting the frontal area as a critical zone for protective measures. Even at the lowest velocity tested (19.0 ± 0.5 m/s), the 900 g UAV generated HIC values indicative of serious injury risk, demonstrating that mass plays a crucial role in the potential for harm, irrespective of speed. The injury risk does not rise linearly with increased velocity; rather, there is a marked nonlinear escalation, particularly evident when the UAV mass is greater. For instance, the transition from moderate to severe injury risk can occur with a relatively small increase in impact velocity.

Comparisons with the AIS scale suggest that even impacts classified as having a 'minimal risk' could have significant consequences for a child, underscoring the need for caution in UAV operation near vulnerable populations. The study's results are instrumental in framing discussions around UAV regulations, especially concerning flight paths in areas frequented by children. It suggests that strict speed limitations and enforced mass restrictions could mitigate the risk of severe injuries. Acceleration duration associated with each impact highlights the importance of temporal factors in head injury criteria, where longer durations at lower velocities can yield similar injury risks to shorter durations at higher velocities.

Future research should investigate the biomechanical consequences of UAVs falling from various heights, focusing on how different fall dynamics affect injury severity. Expanding the range of UAV weights and velocities is essential to understand the risks associated with diverse UAV models. Additionally, studies should simulate real-world scenarios, including the effectiveness of protective gear and UAV collision avoidance technologies, to offer comprehensive insights into injury mechanisms and prevention strategies. This approach will be instrumental in advancing safety protocols for UAV operations, especially in safeguarding children.

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